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PROCESS ENGINEERING II

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PREFACE

Process Engineering deals with the study of phenomena that are applied in production processes in a wide range of industries ranging from the food, chemical, petrochemical and pharmaceutical fields to the building industry. This textbook is intended not only for Process Engineering students studying in English, but also for students studying related fields, not only in Slovakia but also abroad. Readers will become acquainted with heat transfer methods and equipment working on these principles, from heat exchangers, through dryers and evaporators to heat pumps. Another important chapter of this publication covers mass transfer methods and processes such as distillation, rectification, absorption, adsorption and others. A separate chapter is devoted to bioprocesses, in which the reader learns about the microorganisms used in this area, the principle of fermentation processes and the equipment and apparatus in which these processes take place. The last part of the book is devoted to the issue of Safety Engineering and methods of identifying hazards. The publication is supplemented by a number of pictures and diagrams illustrating the individual principles of production processes and equipment in the field of Process Engineering.

We wish everyone pleasant reading.

The team of authors

CONTENTS

1 HEAT TRANSFER

Heat transfer is the transmission of heat energy from a warmer object to a cooler one. Heat processes, for example warming, cooling, condensation and evaporation, are managed by the laws of transfer of heat, which are given in greater detail in the literature dealing with thermodynamics.
In the design of technical equipment, this knowledge is applied in the extent and manner necessary for the given type of equipment.

Heat transfer is a process which is important for each branch of industry. A processed material must be heated to the desired temperature, the heat of the reaction must then be added or subtracted, evaporation heat must be added for the evaporation of fluids or, on the other hand, latent heat must be removed during the condensation of gases and similar operations.

It is often required that heat transfer should be as intensive as possible, while in other cases the reverse is desirable so that the exchange of heat with the environment is as small as possible. Heat transfer has a great importance mostly because, in the majority of operations, energy for heating and cooling has the greatest share among all the energies consumed.

BASIC METHODS FOR HEAT TRANSFER

CONDUCTION

Heat conduction is characterized by heat being passed on a microscopic level: i.e. between the atoms and molecules of a system. Heat conduction is mostly utilized in solid bodies whose various parts are at different temperatures. Through conductivity the heat also spreads in gases and in fluids, where heat transfer also takes place by flowing.

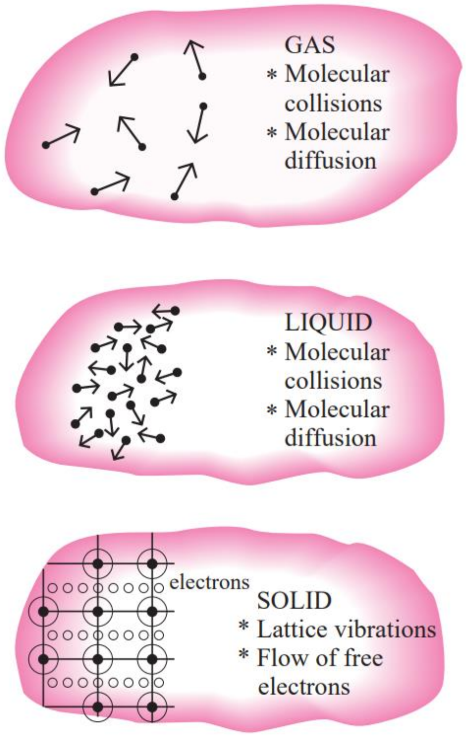


Fig. 1.1. Mechanism of heat transfer by conductivity in a gas, a fluid and a solid body [4]

CONVECTION

Convection occurs in liquids and represents the transfer of energy on a macroscopic level: i.e. among the particles of a liquid containing a great number of molecules or atoms. Convection is always accompanied by heat conduction, while the relative share of both depends on hydrodynamic conditions. In liquids, heat transfer by flowing is substantially faster than by conductivity.

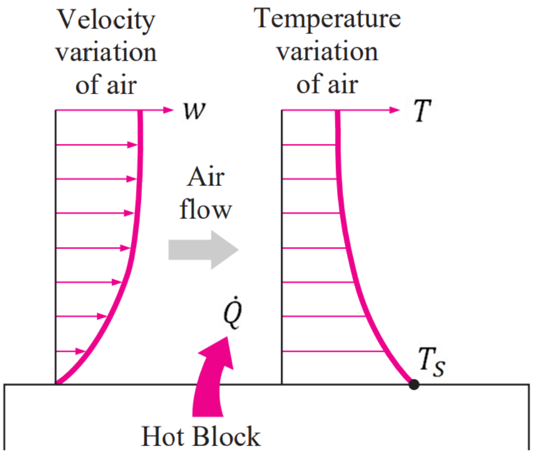


Fig. 1.2. Transfer of heat from the surface of a hot body into air by convection [4]

RADIATION

The transfer of heat by radiation is essentially different from the two preceding methods. With radiation, the heat transfer is in the form of electromagnetic waves, and in contrast to the first two methods a solid environment is not necessary for it to be transferred from one body to another.

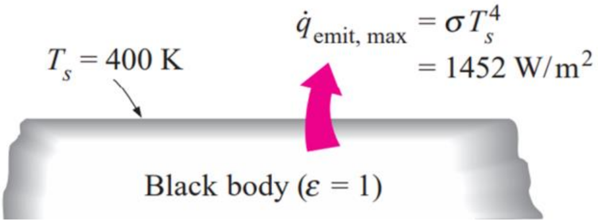


Fig. 1.3. Radiation of a black body giving off heat to the environment [4]

It is important to note that all three mechanisms of heat transfer operate together. Usually one/some of these will be primary, or not occur at all. Figure 1.4 illustrates the situation of cooling a hot body. From the surface of the hot sphere, heat is transferred by ordinary convection (free or forced), while heat is emitted by radiation, which can be felt if the observer is in the proximity of this sphere. The surface of the sphere is cooled by this mechanism, while the core still retains a high temperature. Therefore, heat conductivity moves from the sphere's core to its surface.

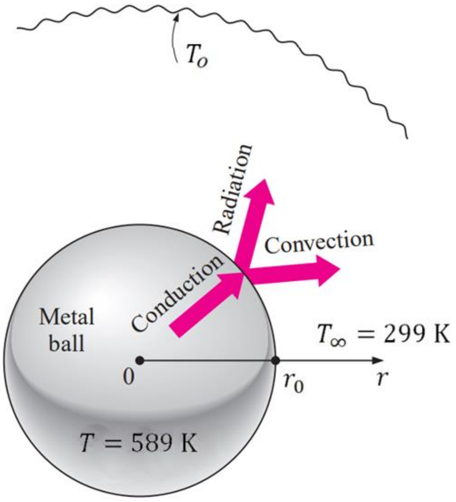


Fig. 1.4. Mechanism of heat transfer in a sphere, and from the surface of the hot sphere to the environment [4]

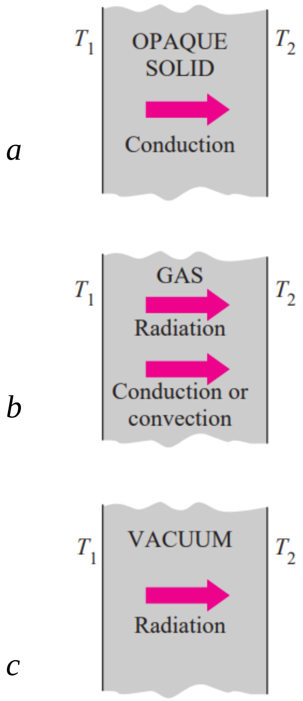


Fig. 1.5 Illustration of the mechanism of heat transfer in various media [4]: a – heat conductivity in an opaque body, b – radiation with conductivity or flowing in a gas, c – radiation in a vacuum

Which mechanism takes place or will be dominant is determined by the environment in which the heat spreads, (Fig. 1.5). In solid bodies, heat is spread by conductivity alone – in a vacuum, just by radiation. Gases, however, absorb radiation only to a slight degree, usually only at certain wavelengths. Ozone, for example, absorbs only ultraviolet radiation. Fluids, on the other hand, absorb radiation very easily, while in gases and fluids all three mechanisms may be effective. Which mechanism takes place or will be dominant is dependent on temperature and hydrodynamic conditions.

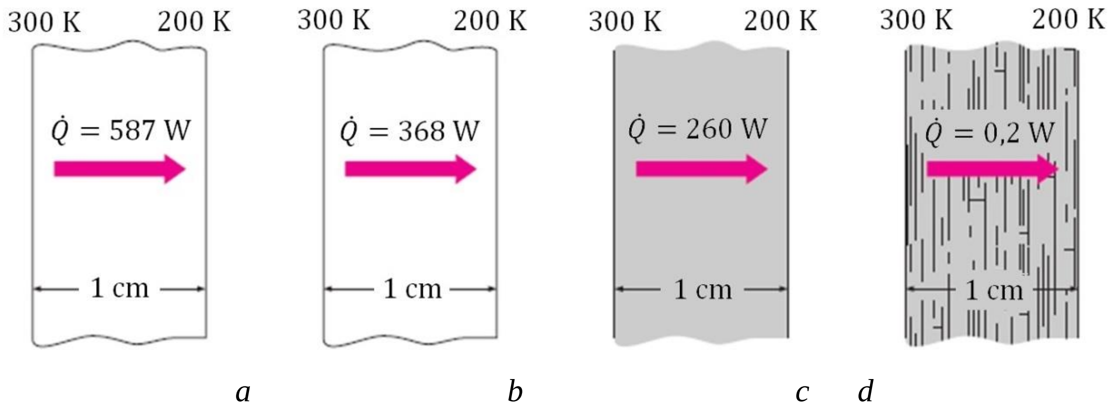


Fig.1.6. Heat transfer in various insulations with a constant area [4]:
a – air, b –vacuum, c – insulation, d – super-insulation

DRIVING FORCE

HEAT TRANSFER BY CONDUCTION AND CONVECTION

The driving force for heat transfer by conduction and convection is the difference of the temperatures between the different points of a system (solid body, fluid, gas), known as the temperature gradient/difference. The heat is spread on a molecular level by the transfer of the energy between the molecules.

With convection it is suitable to make use of the following distinctions:

- *Free /Natural/convection* occurs by the effect of gravitation, and the heat transfer has a vertical direction. Heat rises because the warmer particles of fluids and gases have a smaller density.
- *Forced convection* occurs when the flow is forced (for example by a fan in a room), and then the direction of the transfer of the heat depends on the direction of flow of the liquid.

TRANSFER OF HEAT BY RADIATION

The transfer of heat by radiation is a special case wherein neither convection nor conduction takes place. Heat may also spread by radiation through a vacuum. The intensity of heat radiation depends on certain powers of the temperature of the radiated body. The energy from the sun to the earth for example is transferred by radiation, while the earth disposes of part of the heat by its own radiation.

Each of these three methods of heat transfer may be:

- *Steady (stationary)*

A steady heat transfer is characterized by the fact that at different points in the heat-exchange area the temperatures may be different but do not change over the course of time. Such a phenomenon occurs in continually-operating heat exchangers by the transfer of heat using gas or liquid materials.

- *Transient (unsteady)*

Transient heat transfer occurs very frequently in technical work, mainly in the periodic operation of heating or cooling apparatuses or vessels during the heating, cooling or freezing of materials of a solid physical state. This type of heat exchange is marked by the fact that the temperatures at any point on the particular system change over the course of time.

PRINCIPLE OF CALCULATION OF HEAT TRANSFER

DIRECT HEATING

With direct heating of materials there occurs a mutual relation which is usually accompanied by their mixing. Thus a balanced temperature is achieved throughout the whole mass.

An example of such heating is the direct mixing of water vapour in condensers. In this case condensation of the steam, in other words a phase transfer of water vapour into hot water, normally occurs. The simplest example is the mixing of hot and cold water (Fig. 1.7).

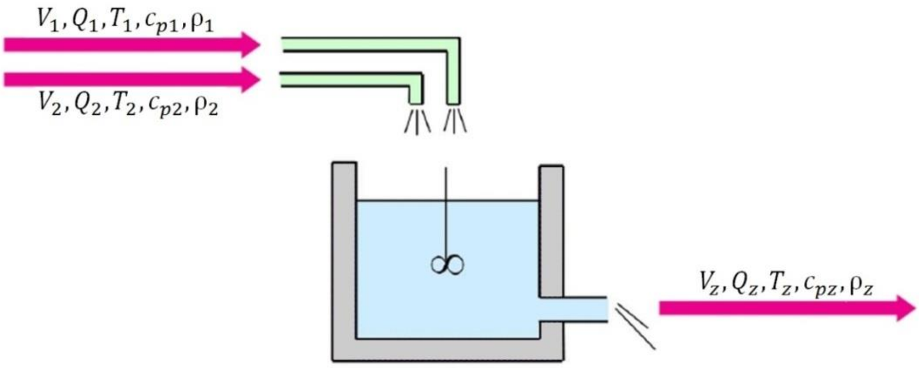


Fig. 1.7. Principle of direct heating or cooling [4]

Fluids of temperatures T_1 and T_2 flow into a vessel from two pipes, with heat capacities at constant pressure c_{p1} and c_{p2}, densities ρ_1 and ρ_2 and flows V_1 and V_2 as is illustrated in figure 1.7. In the vessel is a mixer which assures the mutual mixing of the materials flowing from the pipes. As a result of the mixing of the flowing fluids and the consequent exchange of heat between them , a fluid of temperature T_z flows out of the vessel.

- *Exchange of heat between materials of the same state*

The simplest example of direct heating (or cooling) is the transfer of heat between materials of the same state. This is due to the fact that here no phase change (boiling, condensation, melting, hardening...) takes place, only the transfer of heat from the warmer to the cooler liquid.

This phenomenon can be considered as mixing if the law of retention of energy is applied, in other words if the heat of two or more materials introduced into the system equals the overall heat.

Let n materials with different specific heat capacities and mass flows enter into a system. If each of the heats Q_1 ... Q_n, which is introduced into the mixing vessel by these materials is expressed by the equation

$$Q = m_1\, c_{p1}\,(T_z - T_1) + m_2\, c_{p2}\,(T_z - T_2) + m_n\, c_{pn}\,(T_z - T_n) = 0 \qquad (1.1)$$

where

c_p	–	specific heat capacity at constant pressure of the material	$(\mathrm{J.kg^{-1}.K^{-1}})$
m	–	material mass	(kg)
T	–	temperature	(K)
Q	–	amount of heat	(J)

then the temperature of the mixture T_z is calculated by the equation

$$T_z = \frac{m_1\, c_1\, T_1 + m_2\, c_2\, T_2 + \cdots + m_n\, c_n\, T_n}{m_1\, c_1 + m_2\, c_2 + \cdots + m_n\, c_n} \tag{1.2}$$

- *Exchange of heat between materials of different states*

For example, direct heating of aqueous solutions by saturated steam operates here. The simplest method for heating a fluid, whether water, an aqueous solution or a suspension, is the direct supply of steam. This condenses in the fluid, solution or suspension and gives off its state heat. The condensate mixes with the fluid.

The most basic equipment for this operation is a flexible steam pipe or steam tube, sunk with an open end facing the bottom of the vessel. The condensing steam causes noise, and therefore various modifications are made to the tip of the pipe which, apart from reducing the noise, help to achieve greater temperature uniformity in the total heated volume (Fig. 1.8; Fig. 1.9). This also includes the heating of fluids through flue gases, for which a submersible burner is most commonly used (Fig. 1.10).

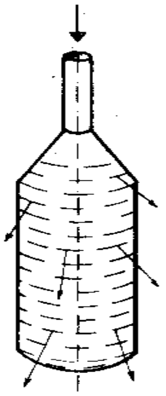


Fig. 1.8. Sparger basket [9]

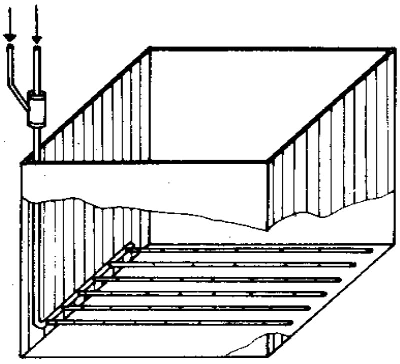


Fig. 1.9. Sparger pipe [9]

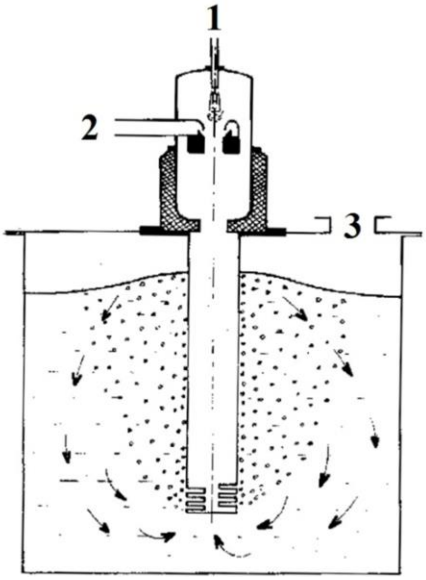


Fig. 1.10. Submersible burner [9]:
1 – fuel entry, 2 – air entry, 3 – flue gas

INDIRECT HEATING

This takes place in a special device called a heat exchanger. In it, the two media are separated by a wall so there is no mutual contact or mixing.

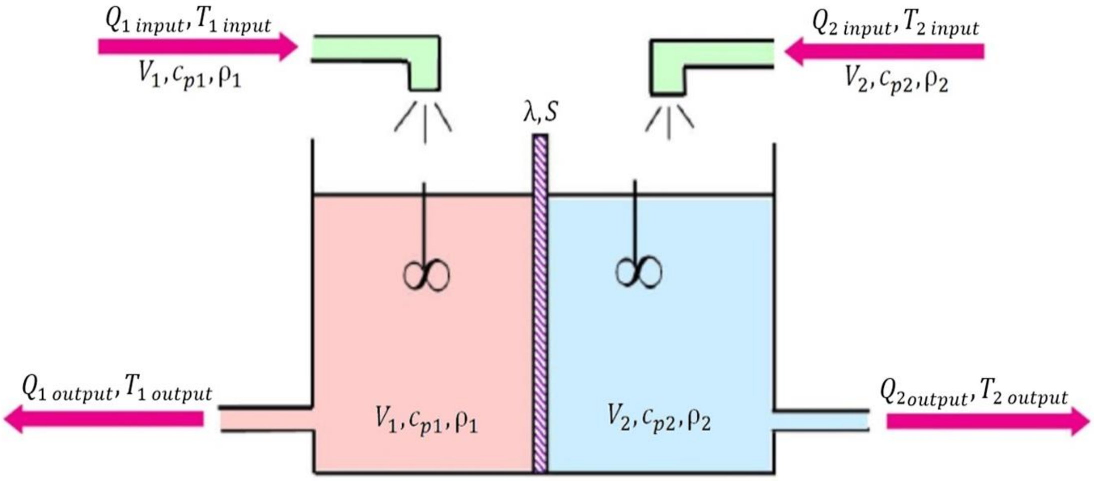


Fig. 1.11. Principle of indirect heating or cooling [4]

In a short summary will be stated the basic relations for the design of a piece of equipment for the exchange of heat where the monitored fluid will be heated or cooled without changing its state and where the exchange of heat is stable (stationary).

The construction of a heat exchanger will be addressed in the following chapter. From the calculation standpoint, the aim is to design a heat exchanger and in particular its heat exchange area (number of pipes, plates etc.). The relations given in a later part of the text represent the normal process of calculation valid for all types of heat exchanger without phase change. In the calculation and design of a specific type of heat exchanger, modifications of these relations must be made for the individual types and are available in the literature. This data also serves as the basis for the construction parameters of a heat exchanger.

As has already been stated, it is necessary to calculate the size of the heat exchange area. This ensures that the liquid exiting from the heat exchanger has the required temperature. An increase or decrease in this final temperature, on the other hand, is achieved by decreasing or increasing the temperature of the heating medium. So the size of the heat exchange area necessary for heating or cooling a liquid by a temperature difference of ΔT_s is calculated from the equation:

$$A = \frac{\dot{Q}}{k\ \Delta T_s} \tag{1.3}$$

where

k	–	overall heat transfer coefficient	$(\mathrm{W.m^{-2}.K^{-1}})$
A	–	heat exchange area	$(\mathrm{m^2})$
$\dot{Q}$	–	heat flow	(W)
ΔT_s	–	mean temperature difference	(K)

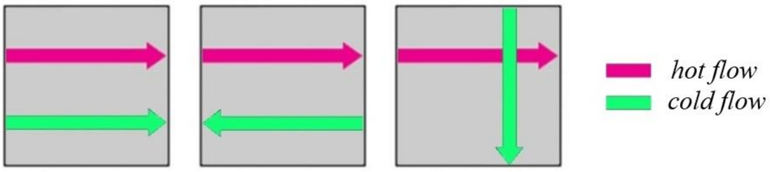
Determining the heat flow is not difficult, and generally it is calculated from the basic heat balance expressed by the equation

$$\dot{Q} = \dot{m}\, c_p\, (T_2 - T_1) \tag{1.4}$$

where

c_p – specific heat capacity at constant pressure $(\mathrm{J.kg^{-1}K^{-1}})$
$\dot{m}$ – material flow $(\mathrm{kg.s^{-1}})$
T_1 – lower temperature (K)
T_2 – higher temperature (K)

A heat exchanger works with two flows, the first heating and the second being heated. If both flows come into the same side and flow in the same direction, such a connection is termed *parallel flow* (Fig. 1.12a). If the flows come into the exchanger on different sides and flow against each other, such a connection is termed *counter flow* or *crossflow* (Fig. 1.12b).



a b c

Fig. 1.12. Arrangement of the flows of a heat exchanger [4]:
a – parallel flow, b – counter flow, c – crossflow

The course variation of the temperatures across the heat exchange area of a simple heat exchanger with a parallel flow connection is shown in figure 1.13 and with a counter flow connection, in figure 1.14. The liquids enter at temperatures $T_1 T_1'$ and exit at temperatures $T_2 T_2'$.

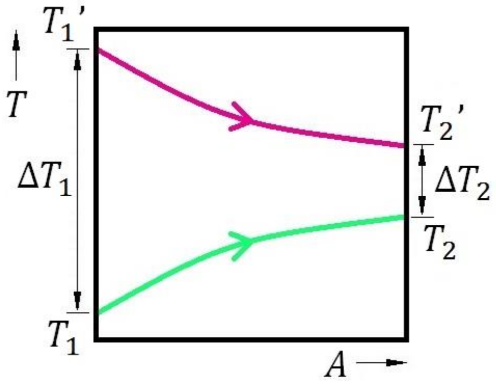


Fig. 1.13. Course of temperatures across a heat exchange area
with parallel flow connection of the heat exchanger [4]

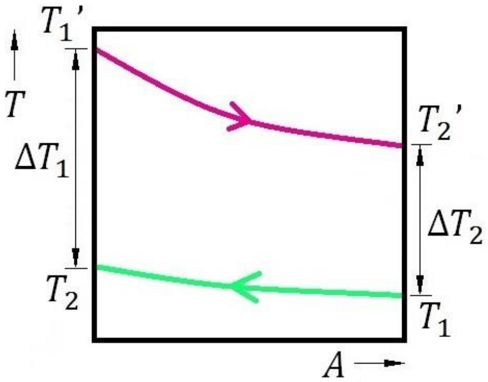


Fig. 1.14. Course of temperatures across a heat exchange area with counter flow connection of the heat exchanger [4]

The mean temperature difference in equation (1.3) may be defined in a number of ways. The two most frequently used are the arithmetical temperature differential ΔT_{ar} and the logarithmic temperature differential ΔT_{ln}.

The mean arithmetical temperature differential ΔT_{ar} is defined by the equation

$$\Delta T_{ar} = \frac{1}{2}(\Delta T_1 + \Delta T_2) \tag{1.5}$$

The mean logarithmic temperature differential ΔT_{ln} is defined by the equation

$$\Delta T_{ln} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{1.6}$$

where

ΔT_1	–	higher temperature differential	(K)
ΔT_2	–	lower temperature differential	(K)

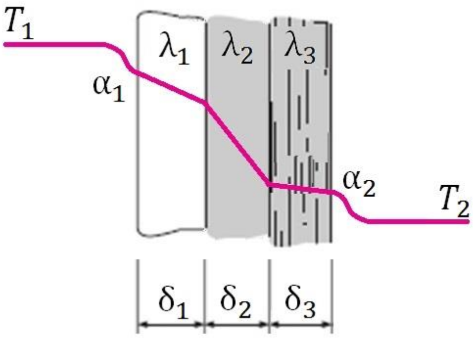


Fig. 1.15.Overall heat transfer coefficient for a plane wall[4]

For the calculation of a heat exchange area, the last value it is necessary to identify is the overall heat transfer coefficient k. In the case of a plane wall (Fig. 1.15), this is defined by the following equation

$$k = \frac{1}{\frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}} \tag{1.7}$$

where

k	–	overall heat transfer coefficient	$(\mathrm{W.m^{-2}.K^{-1}})$
α_1	–	heat transfer coefficient from the liquid onto the wall	$(\mathrm{W.m^{-2}.K^{-1}})$
α_2	–	heat transfer coefficient from the wall to the liquid	$(\mathrm{W.m^{-2}.K^{-1}})$
δ_i	–	thickness of the *i* wall	(m)
λ_i	–	heat conductivity of the *i* wall	$(\mathrm{W.m^{-1}.K^{-1}})$

The heat exchange coefficient is the reciprocal value of the sum of the individual heat resistances, while the resistance of a simple or compound plane wall is the expression $\sum_{i=1}^{n}\frac{\delta_i}{\lambda_i}$.

For a calculation of the heat exchange through a pipe, it is necessary to calculate the linear coefficient of the heat exchange $k_L(\mathrm{W.m^{-1}.K^{-1}})$.

$$k_L = \frac{1}{\frac{1}{\alpha_1 D_1} + \frac{1}{2\lambda}\ln\frac{D_2}{D_1} + \frac{1}{\alpha_2 D_2}} \tag{1.8}$$

where

D_1	–	inside diameter of the pipe	(m)
D_2	–	outside diameter of the pipe	(m)
λ	–	heat conductivity of the pipe wall	$(\mathrm{W.m^{-1}.K^{-1}})$

Where the pipe is composed of i layers of different materials, in the equation (1.8) the transfer of heat by conduction $\frac{1}{2\lambda}\ln\frac{D_2}{D_1}$ is replaced by the expression $\sum_{i=1}^{n}\frac{1}{2\lambda_i}\ln\frac{D_{i+1}}{D_i}$, while the heat exchange coefficient from the wall to the liquid α_2 is dependent on the outside diameter of the top layer D_{i+1}.

Calculation by means of the linear heat exchange coefficient k_L is used for example in the calculation of double pipe heat exchangers, where the calculation of the heat exchange area A is changed to a calculation of the length of the heat exchanger L with the known diameters of pipes D_1 and D_2

$$L = \frac{\dot{Q}}{\pi\, k_L\, \Delta T_s} \tag{1.9}$$

The calculation of the size of the heat exchange area (or length), or the amount of the heat flowing through the given area, is essentially reduced to a reliable determination of the heat exchange coefficients. The equation allowing the calculation of the heat transfer coefficient α must include both the effects of all the physical properties of the liquid and the flow characteristics. The majority of cases of heat exchange are so complex that putting these parameters into one equation on a theoretical basis alone is almost impossible. In this case, a dimensional analysis which allows the grouping of the individual parameters into various non-dimensional groups is very useful. The most important of these for cases of heat exchange are:

- *Nusselt number*

$$Nu = \frac{\alpha\, l}{\lambda} \tag{1.10}$$

- *Reynolds number*

$$Re = \frac{\overline{w}\, l\, \rho}{\eta} \tag{1.11}$$

- *Prandtl number*

$$Pr = \frac{c_p}{\lambda}\eta \tag{1.12}$$

- *Grashof number*

$$Gr = \frac{g\, l^3}{\nu^2}\beta\, \Delta T \tag{1.13}$$

- *Peclet number*

$$Pe = Re\, Pr \tag{1.14}$$

In addition to the expressions stated above

l	–	characteristic dimension	(m)
g	–	gravitational acceleration	$(\mathrm{m.s^{-2}})$
$\overline{w}$	–	velocity of the fluid with respect to the object	$(\mathrm{m.s^{-1}})$
β	–	volume expansion coefficient	$(\mathrm{K^{-1}.})$
ρ	–	density	$(\mathrm{kg.m^{-3}})$
η	–	dynamic viscosity	$(\mathrm{Pa.s})$
ν	–	kinematic viscosity	$(\mathrm{m^2.s^{-1}})$
ΔT	–	temperature differential between the body surface and the mean temperature of the environment (driving force)	(K)

In most general cases for Newton's fluid without change of state, the equation for the calculation of the heat exchange coefficient will have a form according to

$$Nu = f\left(Re; Gr; Pr; \frac{L}{D}; \ldots\right) \tag{1.15}$$

where

D	–	pipe diameter	(m)
L	–	pipe length	(m)

So according to the Reynolds number Re, flow can be divided into laminar, transient and turbulent and according to the Prandtl number Pr, we define the prevailing heat transfer process(conductive or convective). It is clear that a different type of basic equation will be needed for each type of flow or fluid.

In the following part of the text will be stated examples of criteria equations for the calculation of the heat exchange coefficient using the Nusselt number Nu for different fluid flows inside a pipe and between pipes for the straight-line and turbulent flow regimes.

- ***laminar flowing inside pipes***

  For laminar flowing ($Re < 2300$) inside horizontal or vertical pipes, ignoring the effects of convection (natural flowing), the following equation can be used:

$$Nu = 1{,}615\left(Re\,Pr\,\frac{D}{L}\right)^{\frac{1}{3}} \tag{1.16}$$

- ***effect of natural convection***

If a liquid is in contact with a heated wall, natural circulation of the liquid occurs due to the effect of a change of density with temperature. The rapidity of the circulation depends on the shape of the vessel in which the liquid moves and on the arrangement of the heated wall. Just as with forced convection, the Re criterion has the greatest significance; with natural convection the Gr criterion is characteristic. The parameter l in this formula is the linear dimension of the heated surface. With a horizontal cylinder, l is its outside diameter, while for a vertical cylinder or a board, it is usually its height. The mean value of the heat exchange coefficient can be calculated from the dependencies that have a form according to

$$Nu = f(Gr\,Pr\,) \tag{1.17}$$

For example, for *vertical areas*, for the range $10^{-1} \leq Gr\,Pr \leq 10^{12}$it takes the form (1.18), [32]

$$Nu = \left\{0{,}825 + 0{,}387[Gr\,\mathrm{Pr}\,f_1(Pr)]^{\frac{1}{6}}\right\}^2 \tag{1.18}$$

The function $f_1(Pr)$, for area $10^{-3} < Pr < \infty$, is calculated from the equation

$$f_1(Pr) = \left[1 + \left(\frac{0{,}492}{Pr}\right)^{\frac{9}{16}}\right]^{-\frac{16}{9}} \tag{1.19}$$

All of the fluid's physical parameters are replaced with the mean arithmetic temperature of the fluid.

- ***turbulent flowing inside pipes***

For fully developed turbulent flowing, $Re \geq 10^4$ and $0{,}6 < Pr < 160$; $\frac{L}{D} > 50$, the equation below is applied :

$$Nu = 0{,}023\,Re^{0{,}8}Pr^b \tag{1.20}$$

while for cooling $b = 0{,}3$ is applied and for heating $b = 0{,}4$.

- ***forced flowing in pipes under the conditions of transient flow character***

$$Nu = 0{,}116\left(Re^{\frac{2}{3}} - 125\right)Pr^{\frac{1}{3}}\left[1 + \left(\frac{D}{L}\right)^{\frac{2}{3}}\right]\left(\frac{\eta}{\eta_s}\right)^{0{,}14} \tag{1.21}$$

Equation (1.21) is applicable for the range $2300 \leq Re < 10^6$; $0{,}6 \leq Pr \leq 500$; $0 < \frac{D}{L} < 1$.

- ***forced bypass of an individual pipe or bar perpendicular to the axis*** [32]

$$Nu = C\, Re^{n} Pr^{\frac{1}{3}} \tag{1.22}$$

where

n	–	parameter	(1)
C	–	parameter	(1)
Re	–	Reynolds number	(1)

$$Re = \frac{D_v\, w_\infty}{\nu} \tag{1.23}$$

where

w_∞	–	velocity of flow at a sufficiently long distance from pipe surface	$(\mathrm{m.s^{-1}})$
D_v	–	outside pipe diameter	(m)

Table 1.1.Values of constant $C$and n for circular cross-section in dependence on Re value

Re (1)	C (1)	n (1)
0,4 – 4	0,989	0,33
4 – 40	0,911	0,385
40 – 4000	0,683	0,466
4000 – 40000	0,193	0,618
40000 – 400000	0,0266	0,805

It can be seen from the preceding equations that the heat exchange coefficient α depends on many factors and that it is necessary to establish it precisely by using the appropriate criterion equation. However, sometimes for a quick estimate of its value, the values stated in Table1.2 may be used.

Table 1.2 Typical values of heat transfer coefficient

Flow type	α $(\mathrm{W.m^{-2}.K^{-1}})$
Free convection of gases	2 – 25
Free convection of fluids	10 – 1000
Forced convection of gases	25 – 250
Forced convection of fluids	50 – 20000
Boiling and condensation	2500 – 100000

CALCULATION OF EXCHANGE OF HEAT BY RADIATION

This calculation is more complicated than for the preceding heat exchange mechanisms. The basis is the theory of radiation of a completely black body [5]. The radiation emitted by such a body, which depends on the temperature of the body and the emitted wave length, is considered as diffuse and so does not depend on direction. For the most part, these correspond to the materials used and therefore the radiation from them can also be considered as diffuse.

Radiation is a spatial phenomenon and all solid bodies, fluids and gases emit, absorb or release radiation at a certain level [4]. However, for solid bodies radiation is typically considered as a surface phenomenon since they are impermeable to radiation, which is usually absorbed in their top layers.

The maximum radiation flow that can be irradiated from a surface at absolute temperature T_s, is given by the Stefan–Boltzmann law

$$\dot{Q}_{emit\,max} = \sigma\, A_s\, T_s^4 \tag{1.24}$$

where $\dot{Q}_{emit\,max}$(W)is the flow of heat by radiation, and $\sigma = 5{,}67.\,10^{-8}\mathrm{W.\,m^{-2}.\,K^{-4}}$is the Stefan–Boltzmann constant. The radiation flow according to equation (1.24) irradiates a perfect black body (Fig.1.3). The irradiation of real bodies is lower and can be calculated on the basis of a correction of radiation of a perfect black body

$$\dot{Q}_{emit\,max} = \varepsilon\, \sigma\, A_s\, T_s^4 \tag{1.25}$$

where

ε – the emissivity of the surface of a real body. (1)

Table 1.3.Emissivity of certain materials at 300 K

Material	ε (1)
Aluminium foil	0,07
Anodized aluminium	0,82
Polished copper	0,03
Polished gold	0,03
Polished silver	0,02
Polished stainless steel	0,17
Black paint	0,98
White paint	0,90
White paper	0,92 – 0,97
Asphalt pavement	0,85 –0,93
Red brick	0,93 – 0,96
Human skin	0,95
Wood	0,82 – 0,92
Soil	0,93 – 0,96
Water	0,96
Vegetation	0,92 – 0,96

Another significant parameter of radiation is absorbability α, which expresses the ratio between the radiation falling on a body and the radiation that is absorbed. For a black body, its value equals one.

$$\dot{Q}_{incident} = \alpha \dot{Q}_{absorbed} \tag{1.26}$$

Kirchhoff's law states that the emissivity and the absorbability of a body's surface at a given temperature and wave length are equal. In many practical applications, the surface temperature and the temperature of the source of the incident radiation are of an equal magnitude, and the average absorbability of the surface is calculated from its average irradiation. The level to which the surface absorbs the radiation according to figure 1.16 is given by the equation (1.26). The radiation that is not absorbed by the surface is deflected.

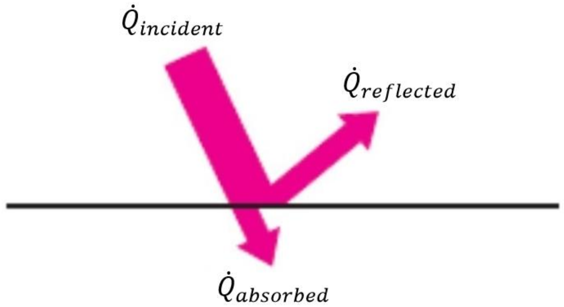


Fig. 1.16. Absorption of incident radiation on an opaque surface [4]

The difference between the radiation emitted by a surface and that which it absorbs represents the net heat transfer by radiation. If the amount of absorbed heat energy is greater than that which is irradiated, the body surface gains energy from the radiation. In the opposite case, it loses energy during radiation.
A more complex situation is when two surfaces are involved, because the heat transfer by radiation depends on both surfaces: on their mutual orientation and on the interaction with the medium that is between them, for example air (Fig.1.17).

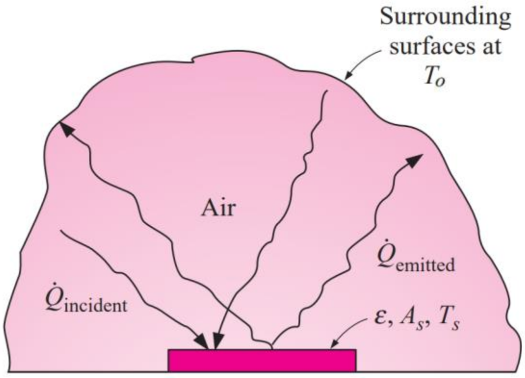


Fig. 1.17.Heat transfer by radiation between two surfaces [4]

If the radiation of the surface is ε, its area $A_s$and absolute temperature T_s, and the body is completely enclosed by another much larger (or black) surface with absolute temperature T_o, and these surfaces are separated by a gas phase (e.g. air), which does not absorb radiation, then the heat transfer by radiation between these two surfaces is given by the equation

$$\dot{Q}_{rad} = \varepsilon\, \sigma\, A_s\, (T_s^4 - T_o^4) \tag{1.27}$$

In this special case, the emissivity of the adjacent surface and the area of the adjacent surface have no effect on the total heat transfer by radiation.

Heat transfer by radiation on or from a surface surrounded by gas works in a similar way to conduction or convection. It should be noted that despite the fact that the gas is not heated from the radiating heat transfer, it is heated from the surfaces emitting or absorbing the heat.

The mechanisms of heat transfer by convection and conduction are then applied in a gas heated in this way. The total amount of heat which is transferred from one surface to a second is composed of the contributions of the heat transfer by radiation, conduction and convection. A simpler calculation uses the combined heat transfer coefficient h_{com}, which includes all these methods of heat transfer.
Then for the calculation it becomes possible to use the equation

$$\dot{Q}_{total} = h_{com}\, A_s\, (T_s - T_\infty) \tag{1.28}$$

Radiation is often similar to conduction or free convection, but is negligible in forced convection, in particular at lower temperatures.

LIST OF SYMBOLS

b	–	parameter of criterion equation	(1)
c	–	specific heat capacity of a material	$(\mathrm{J.kg^{-1}.K^{-1}})$
c_p	–	specific heat capacity at constant pressure	$(\mathrm{J.kg^{-1}K^{-1}})$
c_{pi}	–	specific heat capacity at constant pressure of *i* flow	$(\mathrm{J.kg^{-1}K^{-1}})$
g	–	gravitational acceleration	$(\mathrm{m.s^{-2}})$
h_{com}	–	combined heat transfer coefficient	$(\mathrm{W.m^{-2}.K^{-1}})$
k	–	overall heat transfer coefficient	$(\mathrm{W.m^{-2}.K^{-1}})$
k_L	–	linear heat transfer coefficient	$(\mathrm{W.m^{-1}.K^{-1}})$
l	–	characteristic dimension	(m)
m	–	mass	(kg)
$\dot{m}$	–	mass flow	$(\mathrm{kg.s^{-1}})$
n	–	parameter of equation	(1)
w	–	speed	$(\mathrm{m.s^{-1}})$
w_∞	–	flow speed at sufficient distance from tube surface	$(\mathrm{m.s^{-1}})$
$\overline{w}$	–	average speed	$(\mathrm{m.s^{-1}})$
A	–	heat exchange area	$(\mathrm{m^2})$
A_s	–	size of radiation area	$(\mathrm{m^2})$
C	–	parameter of equation	(1)
D	–	tube diameter	(m)
D_1	–	inside diameter of tube	(m)
D_2	–	outside diameter of tube	(m)
D_v	–	outside diameter of tube	(m)
Gr	–	Grasshof number	(1)
L	–	tube length, tube length of heat exchanger	(m)
Nu	–	Nusselt number	(1)
Pe	–	Peclet number	(1)
Pr	–	Prandtl number	(1)
Q	–	amount of heat	(J)
Q_i	–	amount of heat of *i* flow	(J)
$\dot{Q}$	–	heat flow	(W)
$\dot{Q}_{total}$	–	total heat flow by radiation, convection and conduction	(W)
$\dot{Q}_{emit\,max}$	–	maximum heat flow by radiation	(W)
$\dot{Q}_{rad}$	–	heat transfer by radiation between two surfaces	(W)

Re	–	Reynolds number	(1)
T	–	temperature	(K)
T_i	–	temperature of i wall, temperature of i flow	(K)
T_s	–	surface temperature of a perfectly black body	(K)
T_o	–	surface temperature of ambient body	(K)
T_∞	–	temperature of surroundings of ambient body	(K)
V_i	–	volume of i flow	(m^3)
α	–	heat transfer coefficient	$(\mathrm{W.\,m^{-2}.\,K^{-1}})$
α	–	absorbability	(1)
α_1	–	heat transfer coefficient from liquid to wall	$(\mathrm{W.\,m^{-2}.\,K^{-1}})$
α_2	–	heat transfer coefficient from wall to liquid	$(\mathrm{W.\,m^{-2}.\,K^{-1}})$
β	–	volume expansion coefficient	$(\mathrm{K^{-1}.})$
δ_i	–	thickness of i wall	(m)
ε	–	surface emissivity of real body	(1)
η	–	dynamic viscosity	$(\mathrm{Pa.\,s})$
ν	–	kinematic viscosity	$(\mathrm{m^2.\,s^{-1}})$
λ	–	heat conductivity of tube wall	$(\mathrm{W.\,m^{-1}.\,K^{-1}})$
λ_i	–	heat conductivity of i wall	$(\mathrm{W.\,m^{-1}.\,K^{-1}})$
ρ	–	density	$(\mathrm{kg.\,m^{-3}})$
ρ_i	–	density of i flow	$(\mathrm{kg.\,m^{-3}})$
σ	–	Stefan – Boltzman constant	$(\mathrm{W.\,m^{-2}.\,K^{-4}})$
ΔT	–	temperature difference between body surface and average temperature of surroundings (drive force)	(K)
ΔT_{ar}	–	arithmetic temperature differential	(K)
ΔT_{ln}	–	logarithmic temperature differential	(K)
ΔT_s	–	average temperature differential	(K)
ΔT_1	–	higher temperature differential	(K)
ΔT_2	–	lower temperature differential	(K)

2 HEAT EXCHANGERS

Heat exchangers are technical devices used for enabling the exchange of heat between two, and sometimes even more, media.
Heat exchangers are named according to their function (e.g. heater, condenser, vaporizer), often with the mention of their main operating medium (e.g. oil cooler, steam heater). They are also identified by the type of heat-exchanging area or construction method (e.g. tube heater, finned radiator) or the character of the heat transfer (e.g. mixing condenser, radiation recuperator).

The exchange of heat in heat exchangers occurs through a combined process in which all types of heat exchange mechanisms have their share, i.e. natural and forced convection, heat radiation and heat conduction. In special cases these take place with phase changes. Most frequently these are exchanges with a predominant convection heat exchange component.

DIFFERENTIATION OF HEAT EXCHANGERS

DIRECT HEAT EXCHANGERS

These are heat exchangers in which the exchange of heat occurs through the direct contact of the heat exchange media.

RECUPERATIVE HEAT EXCHANGERS

Also known as recuperators. They are distinct in that the operating media which transfer the heat are separated by a solid wall of elements forming the heat exchange surface.

REGENERATIVE HEAT EXCHANGERS

Also known as regenerators. They are specific in that the heat exchange between the two main materials is provided by a third heat medium (intermediary) which accumulates the heat received from the hotter medium and distributes it to the cooler one.

PRINCIPLE OF HEAT EXCHANGER CALCULATIONS

The design and heat calculation result from the general laws of thermodynamics and fluid mechanics. The significant factors are the pressure losses of both heat transfer media. In their design, issues of solidity are taken into account, and may include the results of temperature dilations, corrosion or the deposition of any undesired material on heat transfer surfaces. In short, attention must be paid to anything that can have an effect on the operating dependability and lifetime of the exchangers. The active heat exchange area of the exchangers is usually created by the connection of a large number of so-called heat exchange elements. Among the most frequently used are cylindrical tubes, normally arranged so that one of the heat-exchange media flows along the tubes.
On the side with the smaller heat transfer coefficient, the surface is deliberately increased by finning; tubes of a circular or rectangular section with external finning form the most frequently used heat-exchange elements (e.g. gas-fluid exchangers). The condition for their correct functioning is good contact between the fins and the base tube.
Greater intensification of heat exchange on both sides is achieved with plate heat exchange elements. By a suitable shaping of the internal profile of the plates, the fluids flow in relatively short canals of small section, often with flow profiles changed in the direction of flow.

A sophisticated element for the construction of heat exchangers are heat tubes with either smooth or finned outer profiles. The intensive exchange of heat is carried out by a suitable heat-exchange medium enclosed inside the tube, which changes its state. In addition, this choice allows the setting of the temperatures at which the heat exchanger operates.
The basic principle of heat exchanger calculations is given in the following section.

The procedure is as follows:

- The heat exchanger type (tube, plate...) is designed in line with the recommendations of specialized literature, according to the properties of the medium that is to be heated or cooled, the character of the technology and the price of the heat exchanger. This is a very challenging step that usually requires significant experience from the designer;
- The setting of the flows is designated (parallel flow, counterflow, crossflow...);
- The amount of heat that it is necessary to transfer between the individual media is calculated according to an equation (1.4);
- The critical relationships for the calculation of the Nusselt numbers for the given type of exchanger and the character of the flow for both media, the heating and the cooling, are researched. From these are calculated the heat transfer coefficient, α_1 and α_2 on both sides of the heat exchange area;
- The calculation of the overall heat transfer coefficient k, to which is added the thickness of the wall of the heat-exchange area and its heat conductivity, along with the heat-exchange coefficients;
- The size of the heat-exchange area is determined (1.3);
- A hydrodynamic calculation is made, with the goal of determining the pressure losses for heating and cooling media flow.

The process calculation is now complete. Since heat exchangers are often pressurized devices, in the further part of the design (which is however outside the scope of this text) the relevant calculations must be performed. The extent of these is set by a standard (for example EN 13445-3).

EFFECT OF IMPURITIES ON HEAT TRANSFER

The overall heat transfer coefficient k, calculated under the condition of a perfectly clean heat exchange area, shows lower values in actual operation. This is due to the layers of deposits and sludge on the material of the heat exchange area.

The layers of deposits and sludge are of two types:

- Layers serving as anticorrosion protection of the construction material, such as immunizing layers, enamel and similar. The thickness of these layers does not significantly change over time but will show a slight wearing as a result of abrasion and corrosion.
- The layers of sludge arising from chemical reactions between the flowing fluids and the wall material, or deposits from clots and sediment. This layer increases over time until the steady state.

Under the condition that the heat transfer coefficients inside and outside tubes α_1 and α_2 are independent of the thickness of the deposits, the heat transfer coefficient of a clean exchanger k_o decreases to the value k_u according to the equation

$$\frac{1}{k_u} = \frac{1}{k_o} + \frac{\delta_u}{\lambda_u} \tag{2.1}$$

where

δ_u – coefficient of the heat conductivity of the deposits $(\mathrm{W.m^{-1}.K^{-1}})$
λ_u – thickness of the deposits (m)

HEAT TRANSFER MEDIA

In much production equipment, it is often necessary to provide the supply and exchange of heat from the heat source to the processed raw material. This takes place by means of heat-transfer media such that the medium accumulates the heat from the heat source into itself and supplies it to the processed raw material in heat appliances. The simplest type of cooling medium and an efficient heat system are chosen according to the parameters of the given processes.

In the selection of the optimal cooling medium, it is necessary to take into account primarily the operating temperature at which the process takes place. The most favorable temperature depends on the heat difference between the heating medium and the heated raw material, in addition to the appliance's heat exchange conditions. The investment costs of the heat exchangers are also important.

The temperature of the heating medium itself determines its type, because the use of the individual media is restricted mainly by the temperature range. If it is possible to choose from among a variety of heat transfer media, among the most important factors in the selection are efficiency and transfer safety.

WATER

The characteristic properties of water suit the requirements for a cooling medium quite well. The relatively significant change of water density at different temperatures has a great effect on natural circulation in a heating system. With increases of temperature the volume of water grows, while its compressibility is negligible. Accordingly, unpressurised systems require expansion vessels and high-pressure systems need pressure regulators. The low viscosity of water is favorable for natural circulation and the high specific heat has an influence on the choice of tubes of relatively small cross section. The heat transfer coefficient from water to the tube wall or from the wall to the water is relatively high.

Systems of heating by water circulation are all based on the same principle – an enclosed circulation cycle. At first the water accumulates heat in the heat exchanger (or heating vessel) and the heat is then transferred to the appliances, where it transfers its accumulated heat to the processed medium. The cooled water is returned to the heater and so circulates permanently in the system. The circulation of the water is either by gravity (gravity circulating heating system) or executed by a pump (forced circulation heating system).

STEAM

In industry, steam is the most frequently used heat transfer medium. A wide range of materials are heated with it where its parameters suit the operating conditions.

- ***wet steam***

  When a steam boiler heats up water, bubbles breaking through the water surface will pull tiny water droplets in with the steam. This will cause the steam supply to become partially wet (wet steam) from the added liquid. The moisture, however, reduces the total heat content and the evaporation heat, and so is not desirable for heating. The water droplets must be removed in a separator before usage, thus giving us saturated steam.

- ***saturated steam***

Saturated steam is an ideal heat exchange medium. It features evaporated (latent) heat, which is released in condensation on heat transfer equipment walls. The exchange of heat from the condensed steam to the heat exchanger wall is great, so the size of the heating area is economical.

- ***superheated steam***

The properties of superheated steam, when considered from the standpoint of a heating medium, are similar to those for gases. The heat transfer coefficient in cooling superheated steam (uncondensed) is relatively small, as with all gases. The heat exchange coefficient is directly proportional to the speed of steam flow along the heating area.

Residual vapours

Vapours originating from evaporation from an aqueous solution, so-called residual vapours, are used for operating heat equipment, usually in the second and further steps in multi-step arrangements. To achieve heat drop, each following step must work at lower pressure than the preceding step. Such arrangements are encountered with evaporators for example. For residual vapours, the heat exchange coefficient can fall significantly due to the contamination of the steam by the gases released from the solution during condensation. For this reason, the heating surface is larger than for well-degassed saturated steam.

A very important part of the heating system is the separator of condensate (steam trap). The function of this equipment is to maintain the whole system at the required pressure and to continuously remove the forming condensate. Improper functioning of the steam trap (badly calculated size, poor maintenance) has a strong effect on the operational efficiency of steam heating equipment.

DIPHENYL MIXTURES

The use of steam as a heating element to achieve higher temperatures (above $200\ °\mathrm{C}$) is problematic because saturated steam reaches pressures greater than $1{,}6\ \mathrm{MPa}$. Equipment working under these conditions is demanding in terms of investment and operation. Therefore, in such cases we can use media which at similar boiling temperatures have much lower pressure than steam. They are available under a variety of trade names, but essentially they are diphenyl mixtures. For comparison we can take $Dowtherm$, which boils $at\ 258\ °\mathrm{C}\ \text{at atmospheric pressure}$, while at this temperature the pressure of the saturated steam reaches $4{,}6\ \mathrm{MPa}$. The manufacturer always states the maximum operating temperature so that decomposition of the heat transfer material does not occur.

MINERAL OILS

The use of mineral oil to transfer heat from the heat source to the appliance at high temperatures comes into question when we cannot use water or steam due to their high pressure, nor direct heating with combustion gases due to the danger of sudden overheating of the product. Although the properties of oil are not particularly advantageous for the transfer of heat,, the fact that their boiling points are high and that oils remain stable up to a certain

temperature bring about their relatively frequent usage. Transfer of heat is only in the form of fluid heat by the artificial circulation of the fluid medium. The normal range of temperatures that work in the system is $300 - 320\ °\mathrm{C}$.
As for all viscous materials, the heat transfer coefficient is quite small and improves at higher temperatures.

COMBUSTION GASES

In equipment for the heating of raw materials with combustion gases, the direct heat resulting from the burning of solid, fluid or gas fuels is used. This manner of heating is encountered wherever higher temperatures unattainable by means of steam or other suitable heating media are required. The relatively small transfer of heat from the combustion gases to the wall of the heating equipment requires a high temperature of combustion gases for the temperature difference, and thus the heat transfer, to be as great as possible.
Inappropriate heating with combustion gases includes cases with a small possibility of regulation of the heat performance, the risk of local overheating and working with an open flame. The large amount of air forming in combustion gases during their dilution results in undesirable oxidation of the apparatus walls.

OTHER WAYS OF HEATING

Among these can be classed heating by molten salts, organic silicates, liquid metals, electric current, fluid beds and others.

TYPES AND DESIGN OF HEAT EXCHANGERS

Heat exchanger designs must comply with wide-ranging requirements for operating technologies, workshop processing and economics. Among the main demands are: a high coefficient of heat transfer (overall heat transfer coefficient), low flow resistance, an easily cleanable heating area, corrosion resistance to various materials, construction adaptability, the weight dictated by production amounts, and the efficient usage of material.
This section describes common types and various designs of heat exchangers, which will be differentiated according to the shape of the heating elements, the method of exchanging heat or the type of heated materials.
The classification of heat exchangers depends on their design and the geometric specifications of the semi-products from which the heat-exchange areas are manufactured. The oldest, and still the commonest, constructional elements are tubes which have diameters of from a few millimeters up to several dozen millimeters. A second product used as a construction element is sheet metal, which can be processed in a number of different ways. Both tubes and sheet metals are made of materials with various chemical compositions, surface treatments and rust-proofing methods.
In the selection of exchangers for specific cases, consideration must be given to whether the proposed type and design is suitable for the given operating conditions. These operating conditions include mainly:

- *operating pressure*

  Operating pressure can vary from a deep vacuum in fractions of Pa up to pressures reaching hundreds of MPa.

- *operating temperature*

  Operating temperatures can vary from values of about absolute zero up to $1000\ °\mathrm{C}$ and even higher.

- *mass flow*

  Mass flow can go from a few grams up to hundreds of kilograms per second.

- *accessibility of heat exchange area*

  Heat exchange area accessibility is indispensable for cleaning and controlling the state of the working areas in contact with aggressive chemicals or heterogeneous suspensions with a tendency to deposits, incrusting and corrosion.

- *sanitation and hygiene*

  The cleanliness of the heat exchanger's area is a specific condition for the food and pharmaceutical industries. In addition to physical cleaning, the required sanitation also includes chemical and bacterial cleaning.

HEAT EXCHANGERS FOR DIRECT HEATING

One of the ways to execute direct heating is the transfer of steam directly to the heating medium. In simple technical equipment, a perforated tube is fully submerged into the heating medium. The optimal positioning of the openings is illustrated in figure 2.1. The openings should not be orientated perpendicularly to the surface because in that case the steam would escape directly upwards and the remainder of the vessel's contents would not be heated. If the openings are directed downwards, the steam escapes from them as small bubbles that gradually condense, and the condensate comes to the surface.

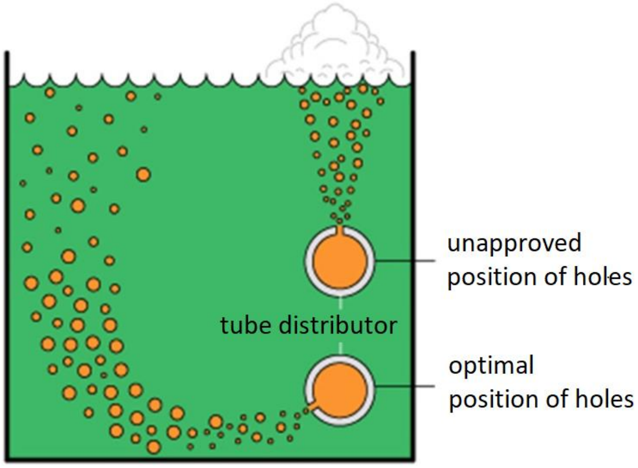


Fig. 2.1. Orientation of the openings in a tube for the transfer of steam [4]

HEAT EXCHANGERS FOR INDIRECT HEATING

There are many designs for the indirect heating of one medium by a second. These depend on the goal of the heating or cooling operation.

- ***Vessel with a heated jacket***

  Vessels of this type have similar operating conditions but they are described according to the character of the technological process: *autoclaves, reactors, nitrators, polymerizers*, *boilers, distillation boilers* and the like. Different technological processes require the processed raw material to be heated or cooled to a given temperature. In reaction processes, heat is to be added or subtracted according to the character of the reaction.

To make the transfer of heat from the wall to the processed raw material more intense, the vessel is often equipped with a mechanical mixer.

Vessels with a heated jacket are mainly cylindrical. The working area of the vessel contains a heated fluid while the wall of this space forms the main shell. Around this shell is found a jacket (also called a duplicator) of a shape similar to the vessel. The space between the wall and the jacket is used for the heating or cooling medium. This medium could be steam or fluid, either water or one of the special media mentioned above.

Figure 2.2 shows a vessel with a heating jacket, where the heating medium is steam. 1 shows the vessel itself and 2 the heating jacket. The steam enters through the inlet 3, and the condensate escapes at 4. 5 is the vent for steam. With a steam-heating jacket, the gap between the jacket and the vessel can be relatively small.

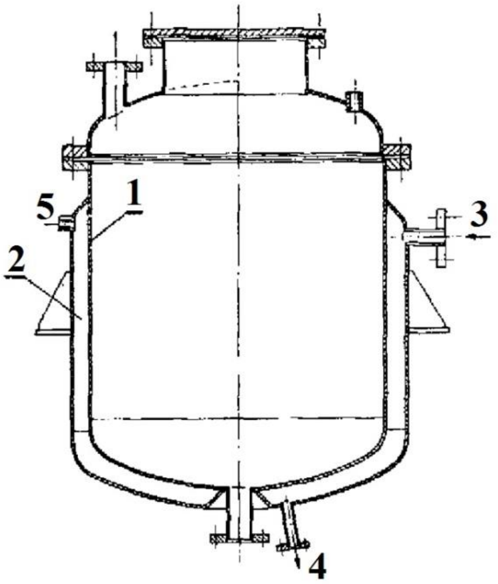


Fig. 2.2. Vessel with jacket heating with steam [9]:
1 – vessel, 2 – jacket (duplicator), 3 – steam inlet,
4 – condensate outlet, 5 – vent

When the jacket heats with a liquid, it is equipped with a welded spiral to ensure better circulation and appropriate flow speed. The spiral ensures better circulation over the whole heating area and excludes dead zones which occur in jackets without circulation spirals. In figure 2.3, 1 is the inlet of the liquid heating fluid, 2 is its outlet, and 3 is the vent. The vessel is equipped with a mixer.

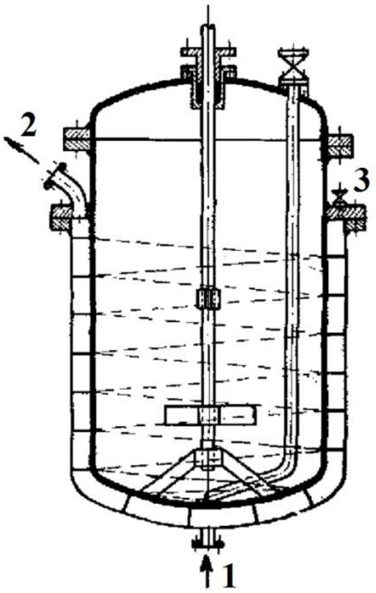


Fig. 2.3. Vessel with jacket heating with liquid [9]:
1 – heating fluid inlet, 2 – heating fluid outlet,
3 – vent

- ***vessels with an external heating coil***

Tanks with internal heating coils, generally using steam as the heating medium, are mainly used for transporting crude oil, oils, liquid chemical products and similar liquids. This heating serves to reduce the viscosity of these fluids during the filling or emptying of the vessels into tankers, tank trucks, or railway tank trucks.

One of the ways to accomplish this heating is by using a set of pipes situated above the floor of the tank (Fig. 2.4). Steam is added through the main inlet and is progressively distributed to the heating pipes through the horizontal steam distributor. Here the steam gives off the heat for heating the liquid in the tank, and condenses.

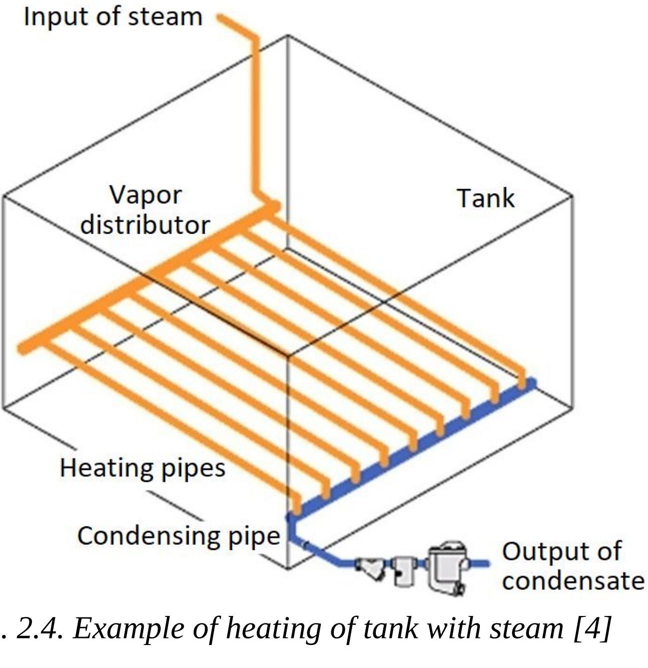


Fig. 2.4. Example of heating of tank with steam [4]

Half-pipe jacketed vessels are mainly used with high temperature heating fluids, as is shown in figure 2.6, or an external heating coil placed on the vessel wall, as in figure 2.7.

Fig. 2.5 Half-pipe jacketed vessel [9]

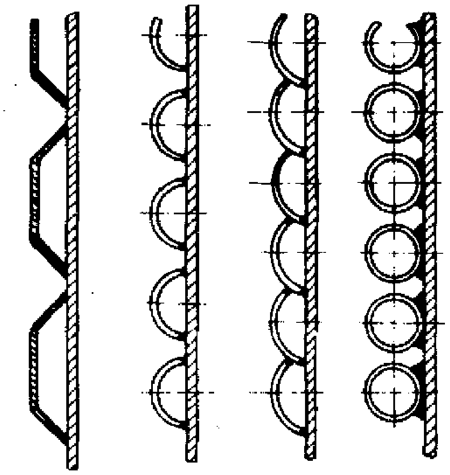


Fig. 2.6.Cross-section of a jacketed vessel with various types of heating elements [9]

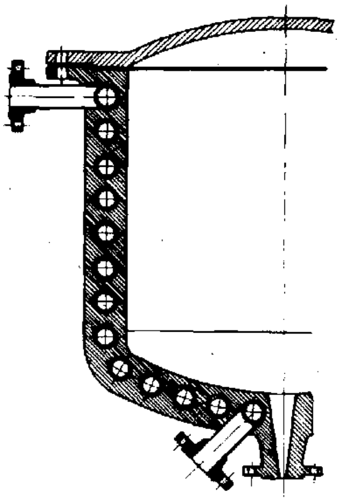


Fig. 2.7.Cross-section of a vessel with an outside heating coil [9]

Vessels with an internal heating coil are used where the heat transfer area is not sufficient for the given task. One or more heating coils are placed in the vessel to increase the heat exchange area and at the same time create a suitable circulation reservoir for a mixer. Figure 2.8 shows equipment without a mixer with twin heating coils. In figure 2.9 is shown twin coil equipment with a mechanical mixer.

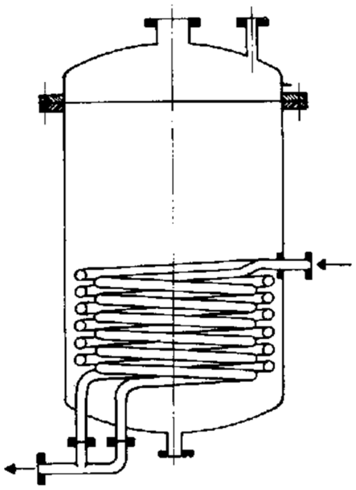


Fig. 2.8. Twin coil vessel, without a mixer [9]

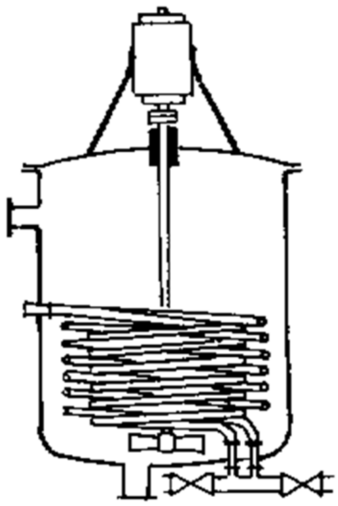


Fig. 2.9. Twin coil vessel with a mixer [9]

- ***double pipe heat exchanger***

This type of heat exchanger is prepared from a pipe equipped with another pipe as a jacket on the outside. The jacket is a pipe with a larger cross-section and is attached to the internal pipe by welding or with a flange. Between both walls of the pipes there is formed an annular space, with the heat-exchange medium flowing through the pipe and the annular space. Such a method of heating or cooling is suitable when it is necessary to clean the exchanger partially in one area. The internal pipe is easily accessible for this purpose.

In practice, a heat exchanger is often made up of several interconnected double pipe heat exchangers. An arrangements of pipes in rows increases the exchange area, while an arrangement in columns allows an increase in the amount of heating (cooling) material. The double pipe heat exchanger in figures 2.10 and 2.11 is assembled with flanged detachable pipe covers.

Fig. 2.10. Double pipe heat exchanger [9]

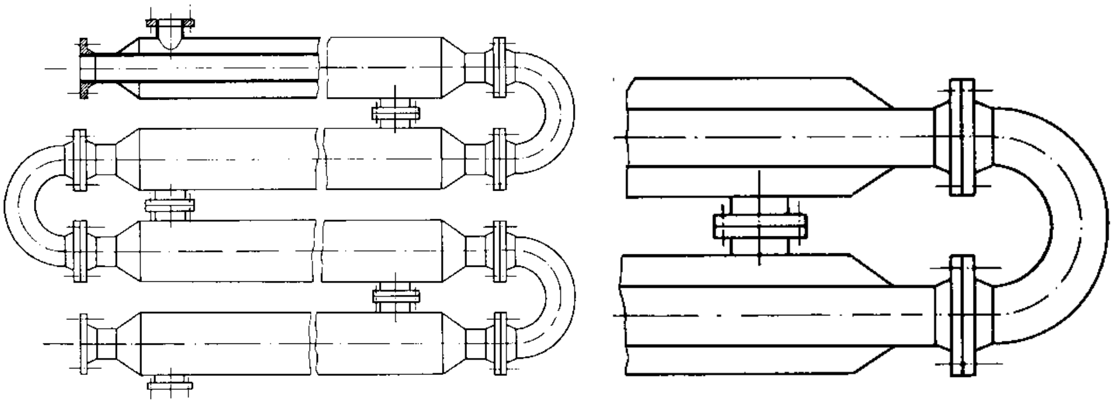


Fig. 2.11. Details of double pipe heat exchanger [9]

- ***Shell and tube heat exchanger***

Double pipe heat exchangers are rather demanding in terms of floor space and so are used only for small or medium outputs. This disadvantage is removed by increasing the number of internal tubes, thus increasing the diameter of the shell. This type of heat exchanger is called a shell and tube heat exchanger.

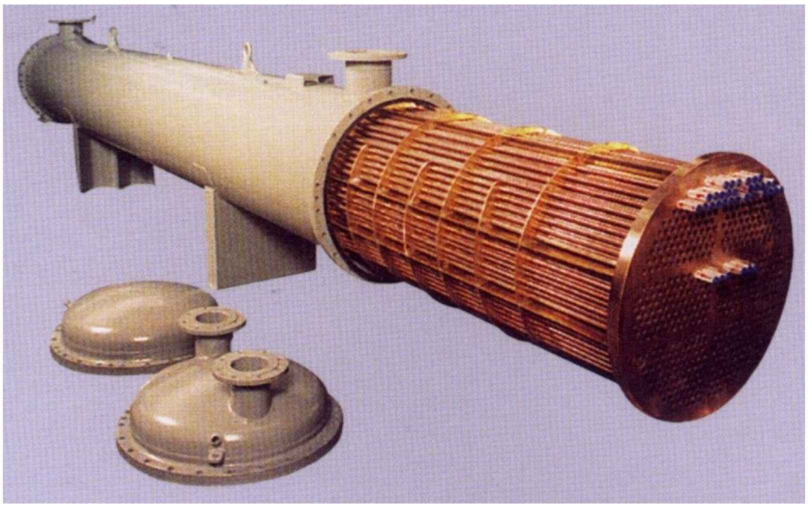


Fig. 2.12. View of an opened heat exchanger with a tube bundle [9]

Figure 2.13 shows a fixed tube sheet heat exchanger. The tubes, fixed in two parallel circular tube sheets by rolling, welding, soldering, or in exceptional cases also by using a seals, can be disposed in triangular, square or circular forms (Fig. 2.14). The most compact method is that whereby the axes of the tubes lie at the top of equilateral triangles, as is shown in figure 2.15.

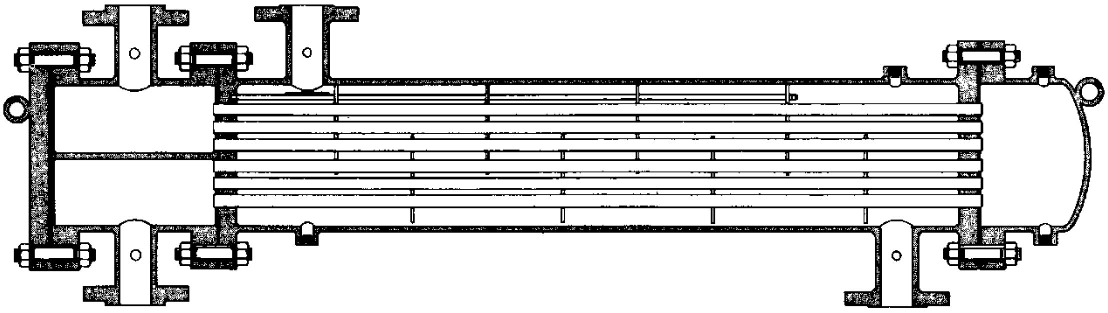


Fig. 2.13. Shell and tube heat exchanger with fixed tube sheet [9]

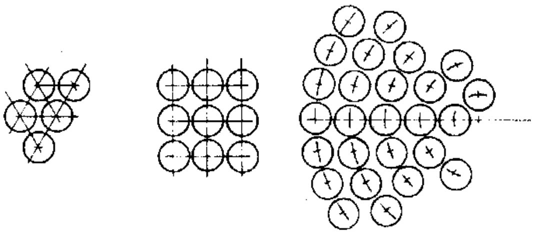


Fig. 2.14. Arrangement of tubes in a tube sheet [9]

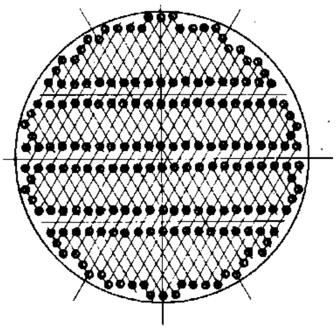


Fig. 2.15. Arrangement of tubes - triangle [9]

It is important to maintain sufficient flow speed for both media, in order to achieve intensive heat exchange and thus economical utilization of the heat exchange area. Therefore, in the space between the tubes, so that the liquid does not change phase (does not condense), there are baffles to prevent the formation of blind spots where the liquid does not move and also to increase its mean speed (Fig. 2.16). The baffles are usually spaced 400 to 500 mm apparat, and they occupy from 60 to 70 % of the jacket inner section area.

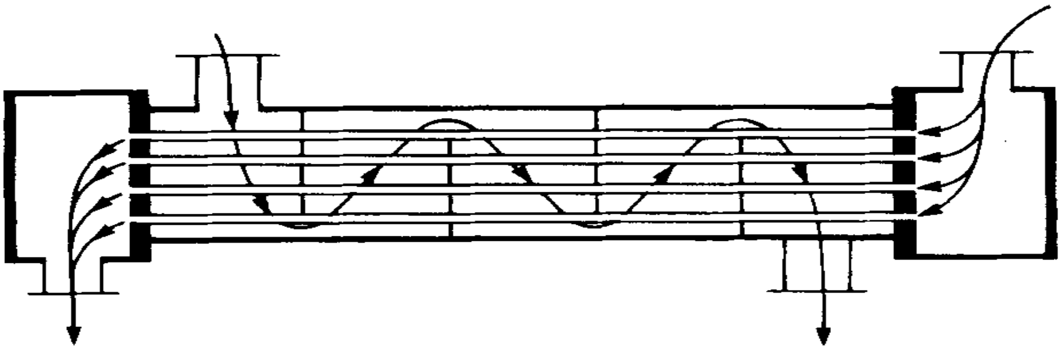


Fig. 2.16. Directing of liquids in the space between the tubes by baffles [9]

Tubular heat exchangers of a jacket type, particularly those with long tubes that feature large temperature differences, must be protected against dilatation. As a result of the thermal expansion of the tubes and the jacket, the tubes bend or the shell deforms, detaching the tubes from the tube sheet. The following devices can be incorporated to combat this risk.

1. Dilatation of the jacket

- *By an expansion joint(compensator)on the heat exchanger shell* (Fig. 2.17),

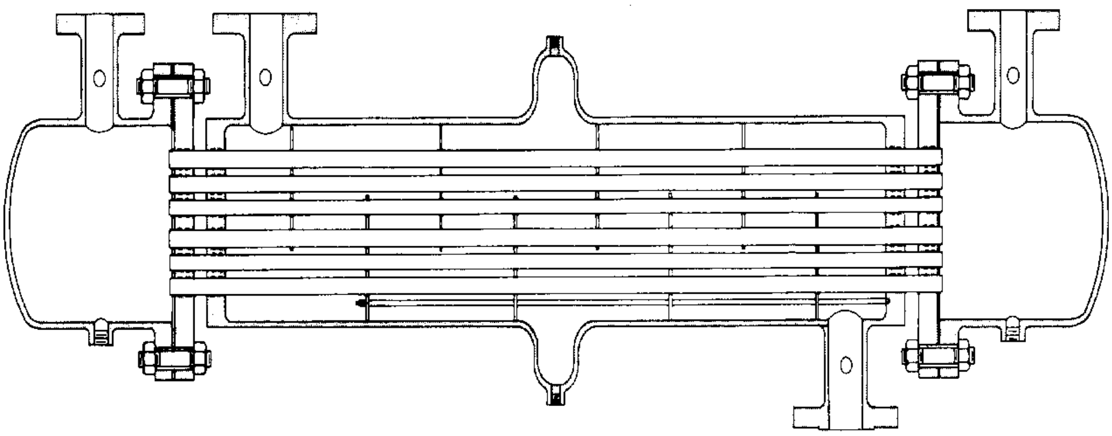


Fig. 2.17. Shell and tube heat exchanger with an expansion joint on the shell [9]

- *By dilatation seals in the heat exchanger shell* (Fig. 2.18),

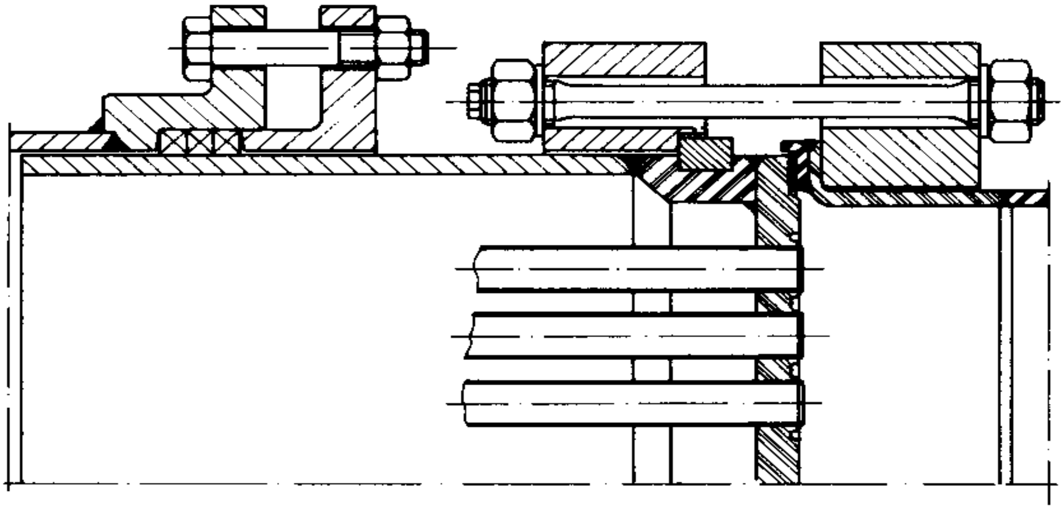


Fig. 2.18. Dilatation seals in the heat exchanger shell[9]

2. ***Arrangement of the tube bundle***

- *heat exchanger with U-tubes* (Fig. 2.19)

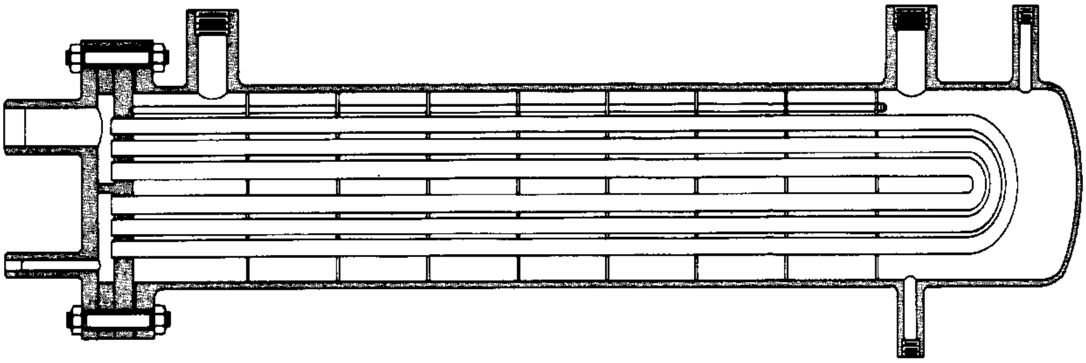


Fig. 2.19. Heat exchanger with U-tubes [9]

A heat exchanger with U-tubes is a vessel made up of a cylindrical jacket containing a removable U- shaped tube bundle secured in a fixed tube sheet. Transversal baffles are placed in the jacket area to direct the flow of the working media and to limit the potential bending of the tubes (in horizontal exchangers). Transversal baffles are soldered into the chamber to separate the flow of the working media in the tube area. These heat exchangers are at least double- coiled.

Fig. 2.20. View of tube sheet and tubes on a U-tube exchanger [9]

- *heat exchanger with a floating head* (Fig. 2.21)

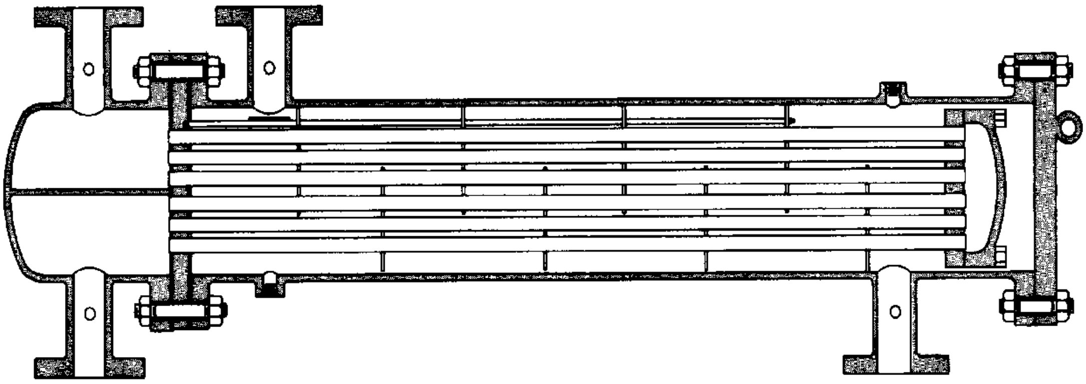


Fig. 2.21. Heat exchanger with a floating head [9]

A heat exchanger with a floating head is a vessel composed of a cylindrical jacket in which is placed a removable bundle of linear tubes secured in one fixed (closed) and one free (floating) tube sheet. Straight baffles are placed in the jacket to direct the flow of the working media and to limit the possible bending of the tubes (in horizontal exchangers). Transversal baffles are soldered onto the chamber to separate the flow of the working media in the tube area. These heat exchangers have at least two coils.

To obtain a larger heat exchange area, it is possible to connect these heat exchangers in series, as is illustrated in figure 2.22.

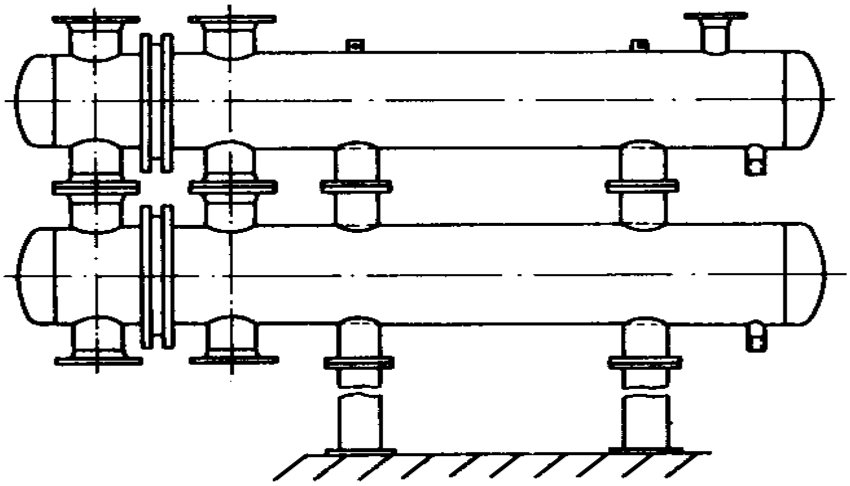
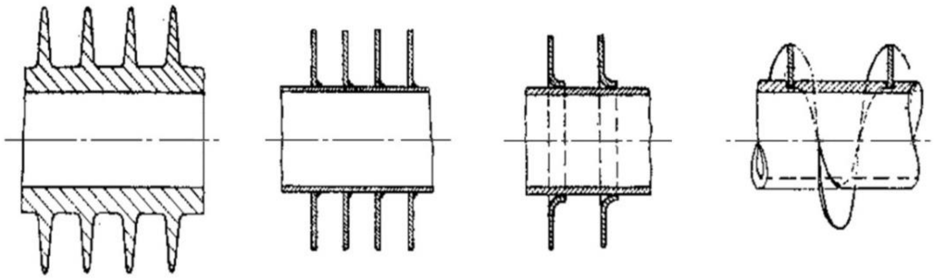


Fig. 2.22 Heat exchangers connected in series [9]

- ***Finned tubes***

During the heating of gases by fluids or condensing steam, the values of the heat exchange coefficient remain high in the case of the heating medium (several thousand $\mathrm{W.m^{-2}.K^{-1}}$), whereas the gas values rarely exceed $50\ \mathrm{W.m^{-2}.K^{-1}}$ even with high gas velocities. This is why we try to expand the tube area on the side of the small exchange coefficient by finning, which considerably increases the overall heat transfer coefficient *k*. The ratio of the finned surface area to the smooth tube ranges from about 10:1 to 20:1.

As regards the material used, finned tubes can be of cast iron, steel, aluminum and its alloys, and non-ferrous metal (copper, brass). As regards shape, the fins can be circular, rectangular, spiral, longitudinal (finned along the tube axis) or in other configurations (Fig. 2.23).



a b c d

Fig. 2.23. Different types of finned tubes [9]:
a – cast-iron finned tube, b – tube with extended or sealed fins,
c – tube with fixed fins, d – tube with spiral wound fins

- ***spiral heat exchangers***

In heat exchangers equipped with tube bundles, it is often difficult to obtain sufficient velocity within the tubes during the exchange between the flowing liquids. In spite of the usage of a multi-speed exchanger (reversal of the flow in the tubes), a sufficiently large heat exchange coefficient *k* is sometimes not achieved.

Relatively good exchange results with equal liquid flow ratios on both sides of the heating area can be achieved with spiral heat exchangers (Fig. 2.24).

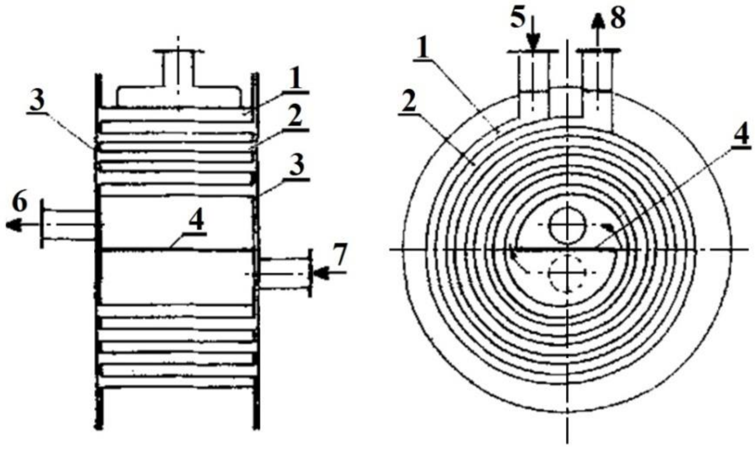


Fig. 2.24. Spiral heat exchanger [9]:
1 – first spiral channel, 2 – second spiral channel, 3 – head of heat exchanger,
4 – intermediate wall, 5 – inflow of first medium, 6 – outflow of first medium,
7 – inflow of second medium, 8 – outflow of second medium

This heat exchanger is made up of two spirals – marked 1 and 2, placed together and so forming continuous channels with a longitudinal cross-section (with the same cross-section along its entire length), whose side walls form two plates, 3. During input and output in the center of the exchanger, both heat-exchange materials are separated from each other by an intermediate wall, 4. On the perimeter wall of the vessel are separate ducts for the inflow of the first medium, 5, and the outflow of the second medium, 8. On the heads of the heat exchanger are located the outflow of the first medium, 6, and the inflow of the second medium, 7. The fluids flow in opposite directions by means of the spirals. Another advantage of this construction is easy cleaning.

- ***plate heat exchangers***

The heat-exchange area of a plate exchanger is made up of parallel, usually vertical, plates arranged in a frame or stand such that slotted channels of widths between 3 and 10 mm are created in the space between the plates. Two fluids flow alternately in these slots, where possible in counter flow. Plate heat exchangers can be characterized as follows:

- The most important element of these exchangers is the working plate, which is a sheet metal pressing from 0,6 to 1,75 mm thick (nowadays most frequently from stainless steel or even titanium);
- The plates provide an exchanger with a total exchange area of up to $600\ \mathrm{m}^2$, and a wide range of flows (from 0,1 to $1000\ \mathrm{m}^3.\mathrm{h}^{-1}$). Due to the relatively high heat-exchange coefficient, they need only a small area per unit of output;
- The range of the working temperatures is from $-10\ °\mathrm{C}$ to $200\ °\mathrm{C}$;
- Operation under hygienic, optimally even sterile, conditions is ensured by the completely closed flow of fluids, and by good sanitation due to the circulation of a cleaning solution. The working area is readily accessible, allowing quick dismantling of the plates bundle for visual control.

In figure 2.25 is shown a plate exchanger whose plates are hung on carriers between two frames, 2 and 3, located laterally by a tie bolt, 5 retaining a pressure plate, 4. The side spaces of the individual plates (Fig. 2.26) are equipped with gaskets that alternately connect the two opposite openings 1 and 2, while opening 3 is flow-through.

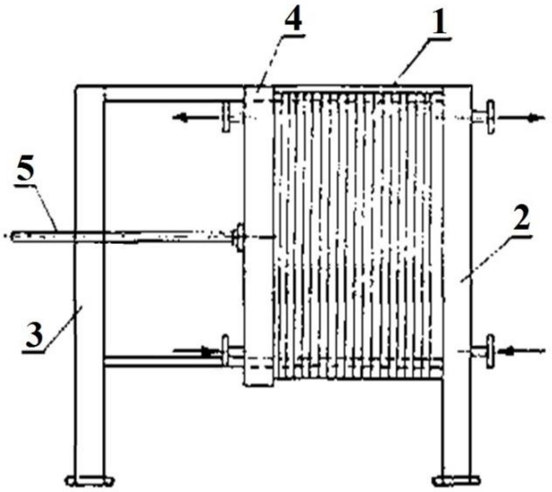


Fig. 2.25. Plate heat exchanger [9]:
1 – plate heat exchanger, 2 – rear frame,
3 – front frame, 4 – pressure plate,
5 – tie bolt

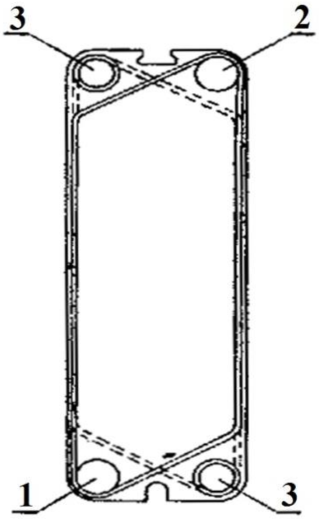


Fig. 2.26. Plate heat exchanger [9]:
1 – input opening, 2 – output opening,
3 – flow openings

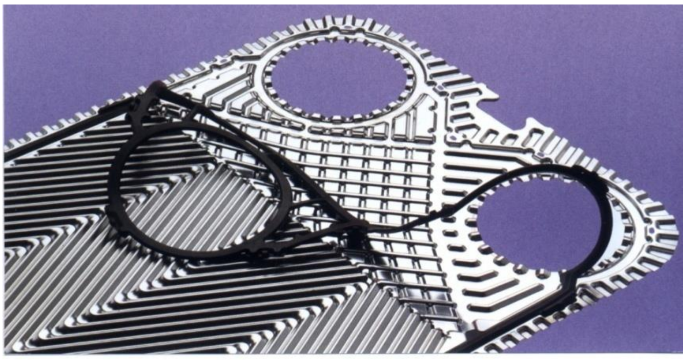


Fig. 2.27. Plate of exchanger with gasket [9]

The heat exchange process is shown in detail in figure 2.29.

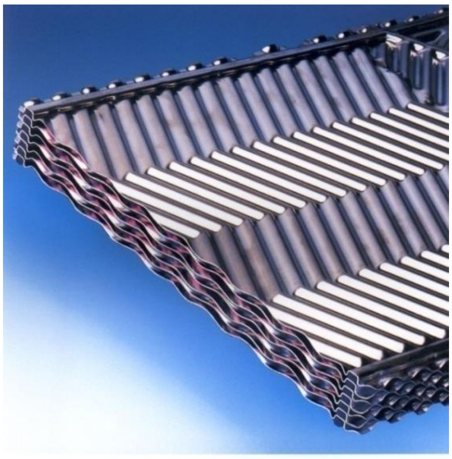


Fig. 2.28. Detail of plates and channels of plate heat exchangers [9]

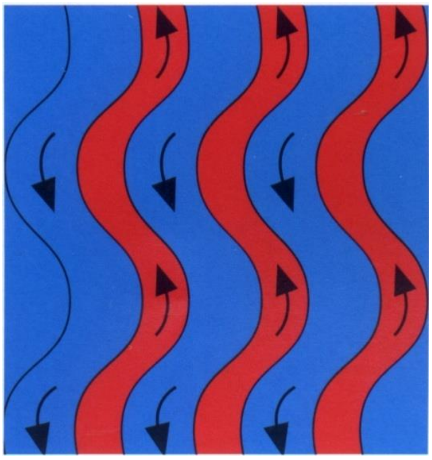


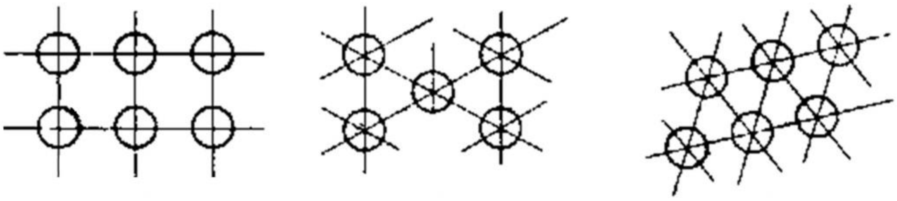
Fig. 2.29. Diagram of flow of hot and cold media in plate heat exchangers [9]

- ***Condensers***

Condensers are heat exchangers where the heat exchange takes place by condensation of the vapours of the fluid. The cooling fluid is usually water, but can be another type of fluid. Its state does not change.

The design parameters of such equipment are similar to that of most heat exchangers. In these devices phase change takes place by the cooling of vapour into fluid. Accordingly, the heat exchange coefficient must be calculated to include film condensation from steam along the wall. The volume of uncondensed gases (most often, air) in the steam greatly slows down the heat exchange. To prevent the massing of inert gases in the condenser, and so a further worsening of the exchange, the uncondensed gases must regularly be sucked out of all condensers.

In horizontal condensers, better heat exchange can be achieved by the correct arrangement of the tubes above each other; this leads to as little of the condensate as possible leaking onto the tubes below (Fig. 2.30).



a *b* *c*

Fig. 2.30. Arrangement of condenser tubes [9]:
a – in line; b – rhombus; c – "Ginabat"

LIST OF SYMBOLS

k – overall heat transfer coefficient $(\mathrm{W.m^{-2}.K^{-1}})$
k_o – overall heat transfer coefficient of clean heat exchanger $(\mathrm{W.m^{-2}.K^{-1}})$
k_u – overall heat transfer coefficient of heat exchanger with deposit $(\mathrm{W.m^{-2}.K^{-1}})$
α_1 – heat transfer coefficient from liquid on the wall $(\mathrm{W.m^{-2}.K^{-1}})$
α_2 – heat transfer coefficient from the wall to the liquid $(\mathrm{W.m^{-2}.K^{-1}})$
δ_u – heat conductivity coefficient of deposit $(\mathrm{W.m^{-1}.K^{-1}})$
λ_u – deposit thickness (m)

3 EVAPORATORS

Evaporation is among the most frequently used operations in inorganic and organic technologies, in the manufacturing of medicines and cellulose, and in the majority of food technologies (confectionery, dairy, fruit juices). The goal of evaporating is to achieve a denser solution in the material, perhaps even crystals. If increased concentration of the dissolved material is not achieved by evaporation, the solution will vaporize at the point of saturation. In this state, the dissolved material is evaporated in the form of crystals. Sometimes evaporation is the result of a chain of mutually dependent separation processes, as in the case of regeneration of organic solvents.

The apparatus in which evaporation takes place is called an evaporator. An evaporator may function in batches (discontinuous) or constantly (continuous), like an open flow system. Discontinuous operations, although having certain advantages, are less favourable in comparison with constant operation, and accordingly we will deal mostly with continuous operation evaporators.

Evaporators may work with atmospheric pressures, either increased or decreased. The input material for an evaporator is a fresh solution, and the product is a densified solution that can be a saturated compound (in this case solid phase crystals are a by-product) and in all cases result in solvent vapours, so-called residual vapours.

Evaporators can be made up of one piece of equipment, known as a single-stage evaporator, or from a series of mutually connected devices known as a multi-stage evaporator (double-stage, triple-stage, multi-stage...).

TYPES OF EVAPORATORS

- ***According to the length and position of tubes***
  - *evaporators with short vertical tubes* (the solution boils inside the tubes, heating is from the external side; these include evaporators of the “Robert” type),
  - *evaporators with medium length vertical tubes* (usually with the boiler placed next to the heating system; these include evaporators of the “Block” or “Wiegand” types),
  - *evaporators with long vertical tubes* (e.g. evaporators of the “Kestner” type),
  - *evaporators with inclined tubes* (with the boiler placed next to the heating system; (e.g. evaporators of the “Vogelbush”, “Buffalo”, “Prache-Bouillon” types).

- ***According to their particular function***
  - *evaporators with natural circulation,*
  - *flow evaporators,*
  - *accelerator evaporators* (based on the original Claassen evaporator),
  - *evaporators with forced circulation,*
  - *accelerator evaporators with forced circulation,*
  - *film evaporators,*
  - *plate evaporators.*

- ***According to the number of stages.***
  - *single-stage evaporators,*
  - *multi-stage evaporators.*

PRINCIPLES FOR DESIGNING EVAPORATORS

SINGLE-STAGE EVAPORATOR

In evaporators of the boiler type, solutions most often evaporate with a tubular heating system in which water vapour is used as the cooling medium. The most common are systems with vertical tubes, where the steam condenses on the inner surface of the tubes and the liquid boils inside the tubes.

In evaporators working continuously, the solution evaporates such that during the process the densified solution of the desired concentration is expelled, and simultaneously enough fresh solution is fed in to maintain a constant volume. Evaporation takes place when the solution is practically at its final concentration, so it has a significantly increased boiling point and high viscosity. This leads to a reduction of the overall heat exchange coefficient. If the residual vapours produced are of a sufficiently high temperature, they may be further used for heating the other stages (in multi-phase evaporation) or other equipment. If the residual vapours are not used as a heating medium, they are passed into the condenser.

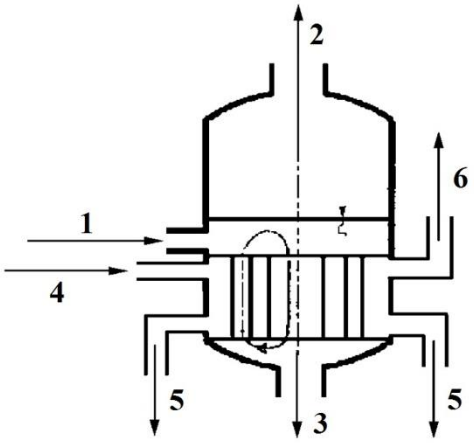
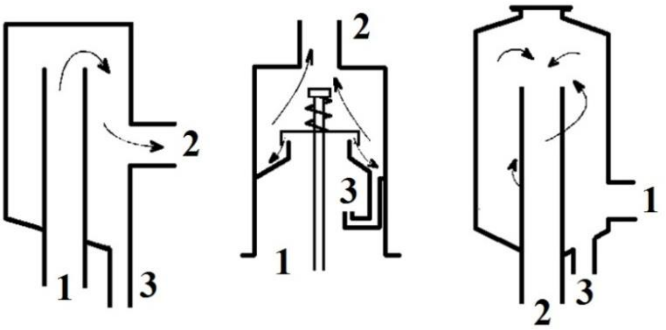


Fig. 3.1. Diagram of single-stage evaporator [9]:
1 – input of fresh solution, 2 – output of residual vapour, 3 – output of densified solution,
4 – input of vapour, 5 – output of condensate, 6 – output of air

The residual vapour that leaves the surface of the solution as a result of the rapid boiling always takes with it a certain amount of the solution in the form of tiny droplets. The escape of the droplets from the solution is a negative phenomenon because they contain part of the reduced material. This leakage can be prevented by the construction of a sufficiently large steam chamber above the level of the solution in the evaporator, or by drop separators situated between the evaporator's steam chamber and the tubes for the removal of residual vapours. The drop separators are based on the principle of the effects of centrifugal or inertial forces on the solution droplets. In figure 3.2 are illustrated the three types of most frequently used separators.



a *b* *c*

Fig. 3.2. Basic types of drop separators [9]:
a – rising, b – deflector, c – tangential,
1 – inflow of waste vapour, 2 – outflow of waste vapour, 3 – outflow of separated drops

- ***material balance***

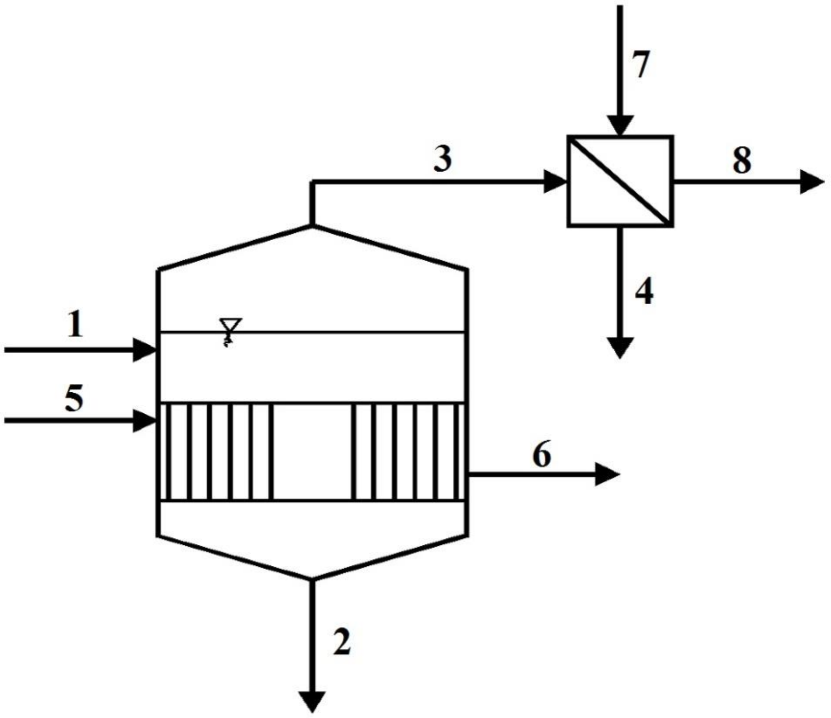


Fig. 3.3. Diagram for material and enthalpy balance of a single-stage evaporator [9]:
1 – input of fresh solution, 2 – output of concentrate 3 – output of residual vapours,
4 – output of condensate from residual vapours, 5 – input of vapour,
6 – output of condensate, 7 – input of coolant, 8 – output of coolant

For a single-stage evaporator working in uninterrupted state without crystallization, from figure 3.3 it follows:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \tag{3.1}$$

where

$\dot{m}_1$ – mass flow of fresh solution $(\mathrm{kg.\,s^{-1}})$
$\dot{m}_2$ – mass flow of concentrate solution $(\mathrm{kg.\,s^{-1}})$
$\dot{m}_3$ – mass flow of residual vapours $(\mathrm{kg.\,s^{-1}})$

For the dissolved compound it follows

$$\dot{m}_1\bar{x}_1 = \dot{m}_2\bar{x}_2 \tag{3.2}$$

where

$\bar{x}_1$ – the mass fraction of the dissolved material in the fresh solution $(\mathrm{kg.\,kg^{-1}})$
$\bar{x}_2$ – the mass fraction of the dissolved material in the densified solution $(\mathrm{kg.\,kg^{-1}})$

- ***enthalpy balance***
  On condition that the heating of the evaporator brings about condensation of the vapour, the enthalpy balance of the device has the form below:

$$\dot{m}_1 i_1 + \dot{m}_p i_p = \dot{m}_2 i_2 + \dot{m}_3 i_3 + \dot{m}_p i_k + \dot{Q}_s \tag{3.3}$$

where

$\dot{m}_p$ – vapour mass flow $(\mathrm{kg.\,s^{-1}})$
i_p – enthalpy of vapour $(\mathrm{J.\,kg^{-1}})$
i_1 – enthalpy of fresh solution $(\mathrm{J.\,kg^{-1}})$
i_2 – enthalpy of densified solution $(\mathrm{J.\,kg^{-1}})$
i_3 – enthalpy of residual vapours $(\mathrm{J.\,kg^{-1}})$
i_k – enthalpy of condensate $(\mathrm{J.\,kg^{-1}})$
$\dot{Q}_s$ – device heat losses (W)

In the uninterrupted state, when the densified solution is not saturated and the mass flows are constant, equation (3.3) can be modified to the form

$$\dot{m}_1 i_1 + \dot{m}_p\left(i_p - i_k\right) = \dot{m}_2 i_2 + \dot{m}_3 i_3 + \dot{Q}_s \tag{3.4}$$

The second element on the left side of equation (3.4) is the heat exchanged between the heated vapour and the solution, expressed by the equation

$$\dot{Q} = \dot{m}_p\left(i_p - i_k\right) = \dot{m}_2 i_2 + \dot{m}_3 i_3 - \dot{m}_1 i_1 + +\dot{Q}_s \tag{3.5}$$

From which, after modification and using equation (3.1), we get

$$\dot{Q} = \dot{m}_1(i_3 - i_1) - \dot{m}_2(i_3 - i_2) + \dot{Q}_s \tag{3.6}$$

In evaporators heated by condensing vapour, the heating apparatus is tubular i.e. it is a tubular heat exchanger, and we can calculate its heating area from equation (1.3). In the evaporation process however, we must take into consideration that the average actual temperature differential $\Delta T_{s,sk}$ is lower than the ΔT_s with heat exchangers. This results in increases in the boiling points of the solutions, in the hydrostatic pressure of the evaporated solution and in the hydrodynamic pressure loss.

The boiling point of the solution is higher than the boiling point of the pure solvent at a given pressure. The effect of hydrostatic pressure of the evaporated solution is exhibited such that the boiling point is higher than at the corresponding pressure of the saturated vapours, a phenomenon which occurs more and more as the pressure in the evaporator goes down. For these reasons, the level of the water in vacuum evaporators should be as low as possible. Pressure loss occurs when the solution flows, resulting in an increased boiling point of the solution.

An increase in the boiling point of the solution occurs especially in high concentration inorganic solutions (e.g., KOH, NaOH, NH_4NO_3). In the case of multi-stage evaporators, this is particularly evident in the later stages.

MULTI-STAGE EVAPORATOR

Most of the heat from the evaporator is taken out by residual vapour, which could be used for evaporation in the second stage if the boiling point of the solution was lower than in the stage from which the steam exits. This would guarantee the temperature difference required for heat transfer. This idea is realized in a multi-stage evaporator consisting of several stages operating at ever lower pressure. This achieves a lower boiling point in a particular stage than in the previous one. The diagram of the parallel flow variant of a three-stage evaporator is shown in figure 3.4.

A fresh solution is fed into the first stage which, after partial concentration, flows into the second stage and from there, by means of a pressure gradient, to the third stage. As a result of the pressure gradient there is also a temperature gradient between the stages, so that the residual vapour from the first stage is used as the heating steam in the second stage, and the residual vapour from the second stage as the heating steam in the third stage. Thus, one kilogram of steam fed into the first stage of a three-stage evaporator evaporates approximately 3 kg of water from the solution. Practically the amount of evaporated water is about 2,5 kg, which causes consumption of heat to warm the solution, as well as heat losses to the environment. The pressure range in which the evaporator works is selected according to how sensitive the solution is to higher temperatures. At higher pressures, the solution has a higher boiling point, and thus lower viscosity, making the heat transfer conditions more favorable.

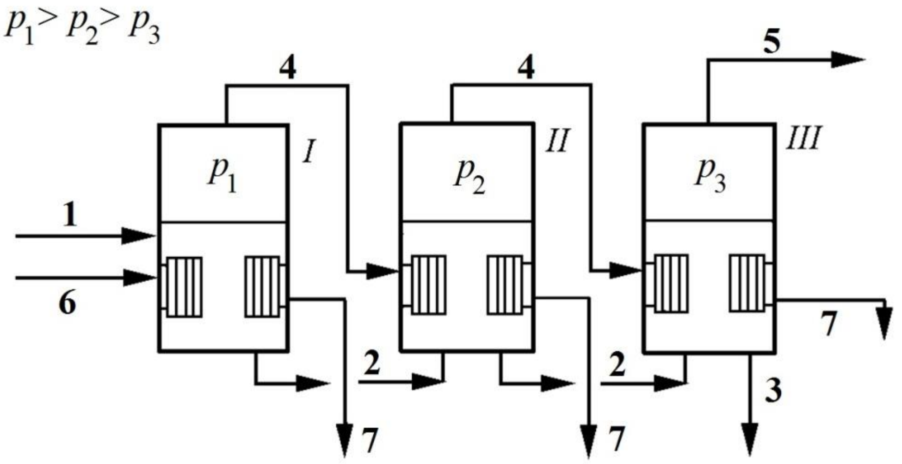


Fig. 3.4. Diagram of the parallel flow variant of the three-stage evaporator [9]: 1 – entry of fresh solution, 2 – solution, 3 – concentrate, 4 – residual vapour, 5 – output of residual vapour, 6 – steam input, 7 – condensate output

Although multi-stage evaporators economize on production, the number of evaporator stages is limited. Their correct number is determined on the basis of an economic balance, including investment and the operating costs for evaporation.

EVAPORATORS TYPES

In industrial practice there are many types of evaporators which are heated by water vapour or the saturated vapours of other materials.

Evaporators heated by vapour can be divided into three groups:

- ***Evaporators with natural solution circulation***

In evaporators with natural circulation, the movement of the solution is caused by the difference in local densities, which is brought about by temperature differences or by vapour bubbles. Such evaporators must be designed to allow sufficiently intensive circulation of the solution. One system frequently used is a central circulation tube. In figure 3.5 is illustrated an evaporator with a vertical heating network. Circulation is provided by a tube of large diameter running through the central circulation system. The circulation of the solution is shown by arrows.

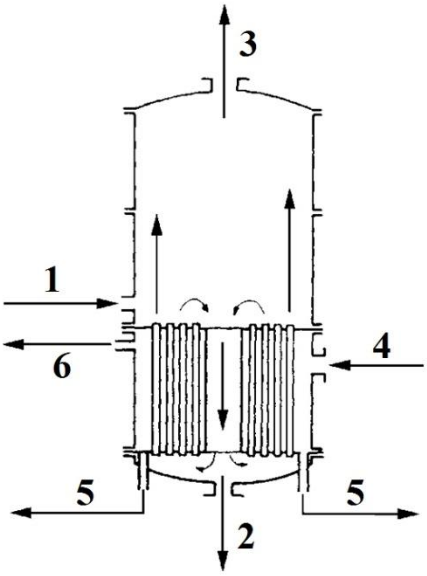


Fig. 3.5. Diagram of an evaporator with a vertical heating network [9]:
1 – input of fresh solution, 2 – output of densified solution, 3 – output of residual vapour,
4 – input of vapour, 5 – output of condensate, 6 – output of air

The evaporators shown in the next three figures have external circulation tubes. These are evaporators with a vertically extended heating network (Fig. 3.6), with a two-stage horizontally extended heating system (Fig. 3.7) and with inclined tube bundle. (Fig. 3.8).

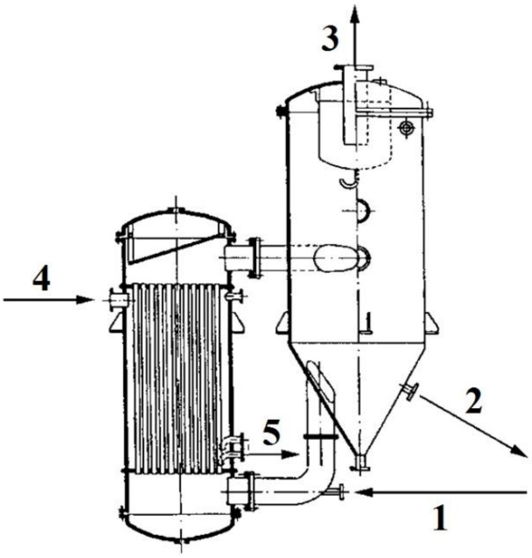


Fig. 3.6. Diagram of an evaporator with a vertically extended heating network [9]:
1 – input of fresh solution, 2 – output of densified solution, 3 – output of residual vapour,
4 – input of vapour, 5 – output of condensate

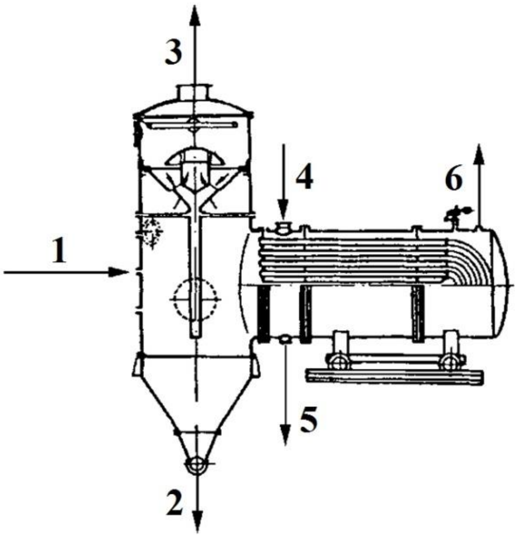


Fig. 3.7. Diagram of an evaporator with
a two-stage horizontally extended heating system [9]:
1 – input of fresh solution, 2 – output of concentrate solution, 3 – output of residual vapour,
4 – input of vapour, 5 – output of condensate, 6 – output of air

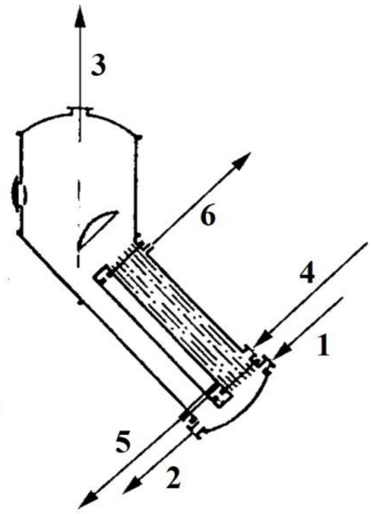


Fig. 3.8. Diagram of an evaporator with an inclined tube bundle [9]:
1 – input of fresh solution, 2 – output of concentrate solution, 3 – output of residual vapour,
4 – input of vapour, 5 – output of condensate, 6 – output of air

These evaporator types have external circulation tubes that are not heated directly, and so the circulation is very intensive. An inclined heating network offers better access to the tubes for cleaning, and the equipment does not have to be so tall.

- ***evaporators with forced solution circulation***

Evaporators with forced circulation use a circulation pump. Figure 3.9 shows such an evaporator with a twin-flow horizontal heating system. Evaporators with forced circulation are appropriate for evaporating high-viscosity fluids, for which natural circulation evaporators cannot be used. The occurrence of encrustation is also slower with such evaporators, due to the intensive circulation of the solution.

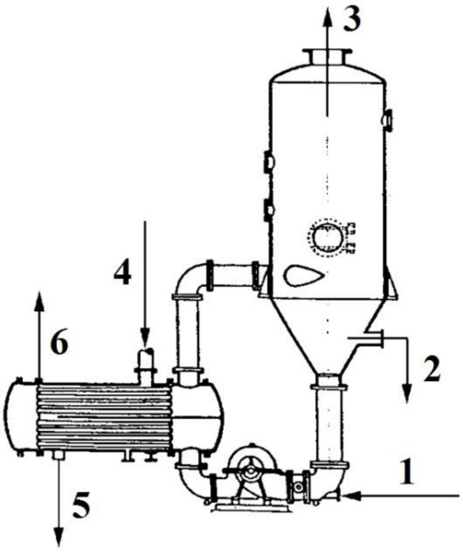


Fig. 3.9. Diagram of an evaporator with forced circulation
and a twin-flow horizontal heating system [9]:
1 – input of fresh solution, 2 – output of concentrate solution, 3 – output of residual vapour,
4 – input of vapour, 5 – output of condensate, 6 – output of air

- ***evaporators with fluid film***

In natural and forced circulation evaporators, the fluid spends a significant amount of time in the boiling area. In periodically-working equipment this can be a matter of several hours, with continuous flow, about one hour. This is due to the fact that the volume of fluid amounts to a multiple of the volume flow of the fresh solution. This is unfavourable with solutions undergoing the effect of heat, for example fruit juices, blood plasma, animal extracts, vitamins, and the like. With these materials, contact with the heat exchange area must be limited to a very short time to avoid the risk of their degradation.

This short contact time is achieved by creating a thin fluid film in film evaporators. In figure 3.10 an evaporator with a Kestner capillary film is illustrated. It is composed of a long network of tubes, with the raw solution fed to their base. The mixture of fluid and steam is forced upwards at significant speed because in the long tubes there occurs rapid evaporation, along with a significant formation of steam drawing in the fluid in the form of a thin coating (film) along the walls of the pipes. Both the fluid and the vapour enter the separator from side feeds.

This type of evaporator is used for dense and foamy solutions. It is not appropriate for encrusting solutions due to cleaning issues. The advantage of an evaporator with a capillary film is the fact that increased boiling temperatures caused by hydrostatic pressure in the heat column in the evaporator do not occur. However, they are not suitable for evaporating high-viscosity fluids.

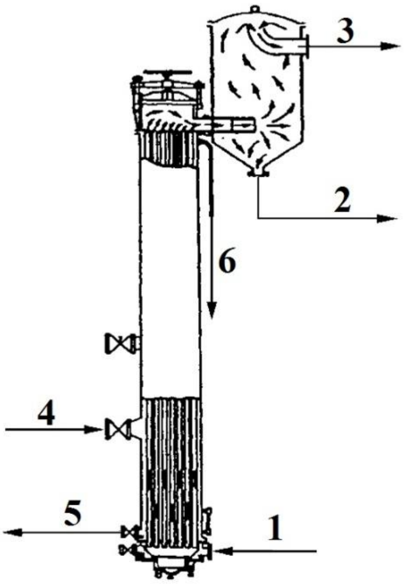


Fig. 3.10. Diagram of an evaporator with a Kestner capillary film [9]:
1 – input of fresh solution, 2 – output of densified solution, 3 – output of residual vapours,
4 – input of vapours, 5 – output of condensate, 6 – output of air

In order to use a film evaporator for high-viscosity fluids, evaporators with a wiped film have been built. The fluid film is created by rotating blades of various designs. The thickness of the fluid film is dependent on the viscosity of the fluid, and ranges from 0,1 mm to 1 mm. In figure 3.11 is shown an evaporator with a film wiped by various types of wiper blades.

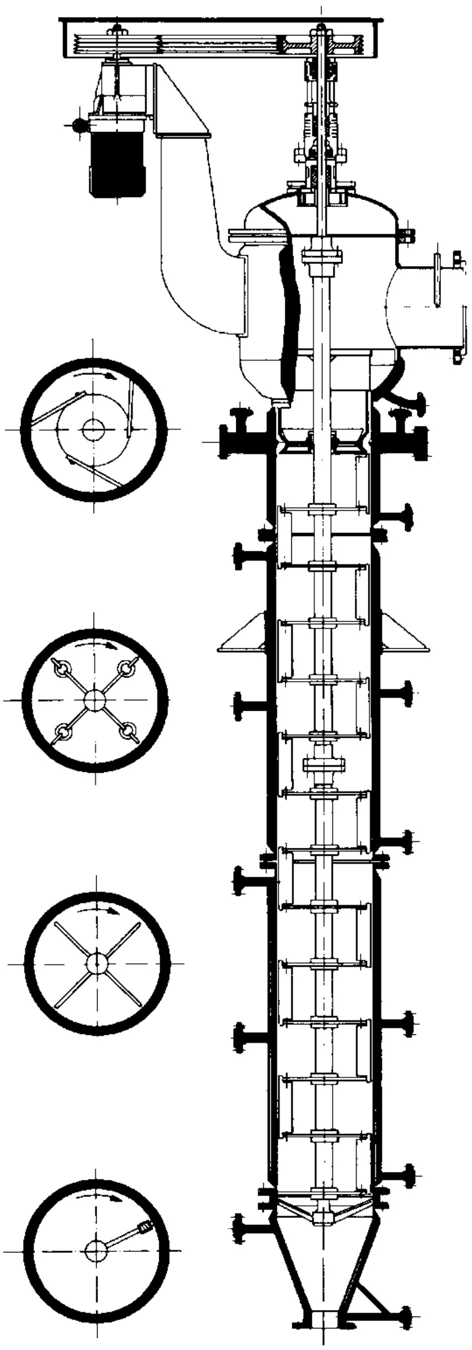


Fig. 3.11. Diagram of a wiped film evaporator [9]

LIST OF SYMBOLS

i_k – enthalpy of condensate $(\mathrm{J.kg^{-1}})$
i_p – enthalpy of vapour $(\mathrm{J.kg^{-1}})$
i_1 – enthalpy of fresh solution $(\mathrm{J.kg^{-1}})$
i_2 – enthalpy of densified solution $(\mathrm{J.kg^{-1}})$
i_3 – enthalpy of residual vapour $(\mathrm{J.kg^{-1}})$
$\dot{m}_p$ – mass flow of vapour $(\mathrm{kg.s^{-1}})$

$\dot{m}_1$ – mass flow of fresh solution $(\mathrm{kg.\,s^{-1}})$
$\dot{m}_2$ – mass flow of densified solution $(\mathrm{kg.\,s^{-1}})$
$\dot{m}_3$ – mass flow of residual vapours $(\mathrm{kg.\,s^{-1}})$
$\bar{x}_1$ – mass fraction of dissolved material in fresh solution $(\mathrm{kg.\,kg^{-1}})$
$\bar{x}_2$ – mass fraction of dissolved material in densified solution $(\mathrm{kg.\,kg^{-1}})$
$\dot{Q}$ – heat flow (W)
$\dot{Q}_s$ – equipment heat losses (W)

4 DRYERS

Drying is understood as the physical process by which the content of the fluid in materials (over 99 percent of the applications involve the removal of water) is reduced by the effect of heat without changes to their other chemical properties. The fluid is removed by evaporation, vaporization or sublimation. The removal of fluid from materials by a method other than heat (mechanical dewatering operations such as filtration, centrifugation, sedimentation or chemical methods) is not considered to be drying. Therefore, the purpose of the drying process is to reduce the content of fluid in the drying material with an accompanying change in its technological properties:

- achieving the determined physical-chemical properties (chemical products),
- improving the structural and heat properties of the material (wood, ceramics, construction materials, insulating materials and the like),
- increasing heating properties and improving burning (fuels),
- improving conservation capacity (agricultural and foodstuff products),
- improving biochemical properties (grains, seeds).

Drying is a very widespread technological process, applied in almost all industrial branches. In the chemical industry it represents one of the most important basic operations.

THE THEORY OF DRYING

Drying is a complex operation involving transient transfer of heat and mass along with several rate processes, such as physical or chemical transformations, which, in turn, may cause changes in product quality as well as the mechanisms of heat and mass transfer. The theory of drying is accordingly based in essence on two scientific branches - the theory of heat and mass transfer and the theory of moisture content in a material. It investigates the speed of drying and the effects which the parameters of the material to be dried and the drying environment have on it.

HEAT AND MASS ENERGY BALANCE OF DRYING

This presents the relationship between the quantities characterizing the initial and final parameters of the material included in the drying process. Mainly the mass and energy balance of the drying process.

DYNAMICS OF DRYING

This determines the relationship between the change in moisture of the material to be dried and the drying parameters. So it generally determines a change in the moisture of the material to be dried at a given place and time, in dependence on the specific moisture, the differences of the temperature in the material, the type of drying, and the type and construction of the dryer. If all the necessary relations are not known, the change of the average moisture of the material is monitored in dependence on the parameters of drying. Sometimes this part of drying theory, which essentially belongs to the dynamics of drying, is referred to as *drying kinetics*.

EXTERNAL AND INTERNAL CONDITIONS OF DRYING

The conditions under which we bring the heat necessary to remove moisture are called the external conditions of drying. These are given by the aerodynamic and thermodynamic balance in the drying area and can be influenced by the selection of the drying method, the design of the dryer and the regulation of the drying process.

The internal conditions of drying are characterized by the connection between the moisture in the material and its movement within the drying material. These are dependent on the nature of the material to be dried and can only be influenced to a limited extent. Among these are the structure and form of the material, the physical properties of the dry matter and the moisture, and the material's ability to transfer heat and moisture.

DRYING MEDIUM

The heat supply required to remove moisture can be by any of the heat transfer mechanisms - convection, conduction or radiation. These may include, for example, high-frequency, microwave, dielectric, induction or resistance heating, singly or in combination. For removing moisture from the surface, it is necessary to have a drying medium which absorbs moisture in the form of vapour.

In technical practice, the most usual drying medium is air and the most usual moisture is water. The design of the dryer therefore must ensure that the air flows through the dryer in such a quantity and state that it is capable of absorbing the complete amount of evaporated water. With convection dryers there is the added requirement that the air transfer a sufficient amount of heat to the drying material.

PSYCHROMETRIC CHARTS /MOLLIER DIAGRAM/

The air used as a drying environment is a mixture of dry air and water vapour, so-called moist air. The physical parameters of moist air are graphically illustrated in psychrometric charts. The diagram will be called *the i - Y psychrometric chart* (in the literature we also find the designation *i - x; h - x; h - Y*) and it is shown in figure 4.1.

In the i - Y diagram these parameters are clearly readable:

- ***on the horizontal axis the content of water vapour in* 1 kg *of* *dry air is* Y**

  The content of water vapour Y (sometimes known as absolute moisture) in the air cannot be random.

- ***on the vertical axis the heat content (enthalpy) of moist air is i, dry bulb temperature T and the wet bulb temperature T_m***

  The heat content i is made up of the heat content of dry air and the heat content of the water vapour.

$$i = c_{pv}\, T + Y\left(r_0 + c_{pvp}\, T\right) \tag{4.1}$$

where

i	–	enthalpy of moist air	$(\mathrm{J.kg^{-1}})$
c_{pv}	–	mean heat capacity of the air	$(\mathrm{J.kg^{-1}K^{-1}})$
T	–	temperature of the air	(K)
Y	–	content of water vapour in 1 kg of dry air	$(\mathrm{kg.kg^{-1}})$

r_0	–	evaporation heat of water at temperature 0 °C	$(\mathrm{J.kg^{-1}})$
c_{pvp}	–	mean heat capacity of vapour	$(\mathrm{J.kg^{-1}K^{-1}})$

Dry bulb temperature (DBT) T is measured by an ordinary thermometer.

Wet bulb temperature (WBT) T_m is the temperature read by a thermometer covered in water-soaked cloth a wet bulb thermometer), over which air is passed. At 100 % relative humidity, the wet bulb temperature is equal to the air temperature (dry bulb temperature) and it is lower at lower humidity. It is defined as the temperature of a parcel of air cooled to saturation (100 % relative humidity) by the evaporation of water into it, with the latent heat supplied by the parcel. The wet-bulb temperature is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only.

- ***relative moisture* φ *from* 0 *to* 100 %**

Relative moisture φ is the ratio of the partial pressure of the water vapour found in the air to the partial pressure of steam during saturation. It is depicted by curves, with the lower curve shown as 1,0 (or 100 %) and called the limit curve or curve of saturation. The area under the limit curve is called the mist area; the air here is saturated by the liquid phase.

- ***dew point***

The dew point temperature is the temperature at which the air is maximally saturated by water vapours (the relative moisture of the air is 100 %). If the air temperature dips below this value, condensation occurs.

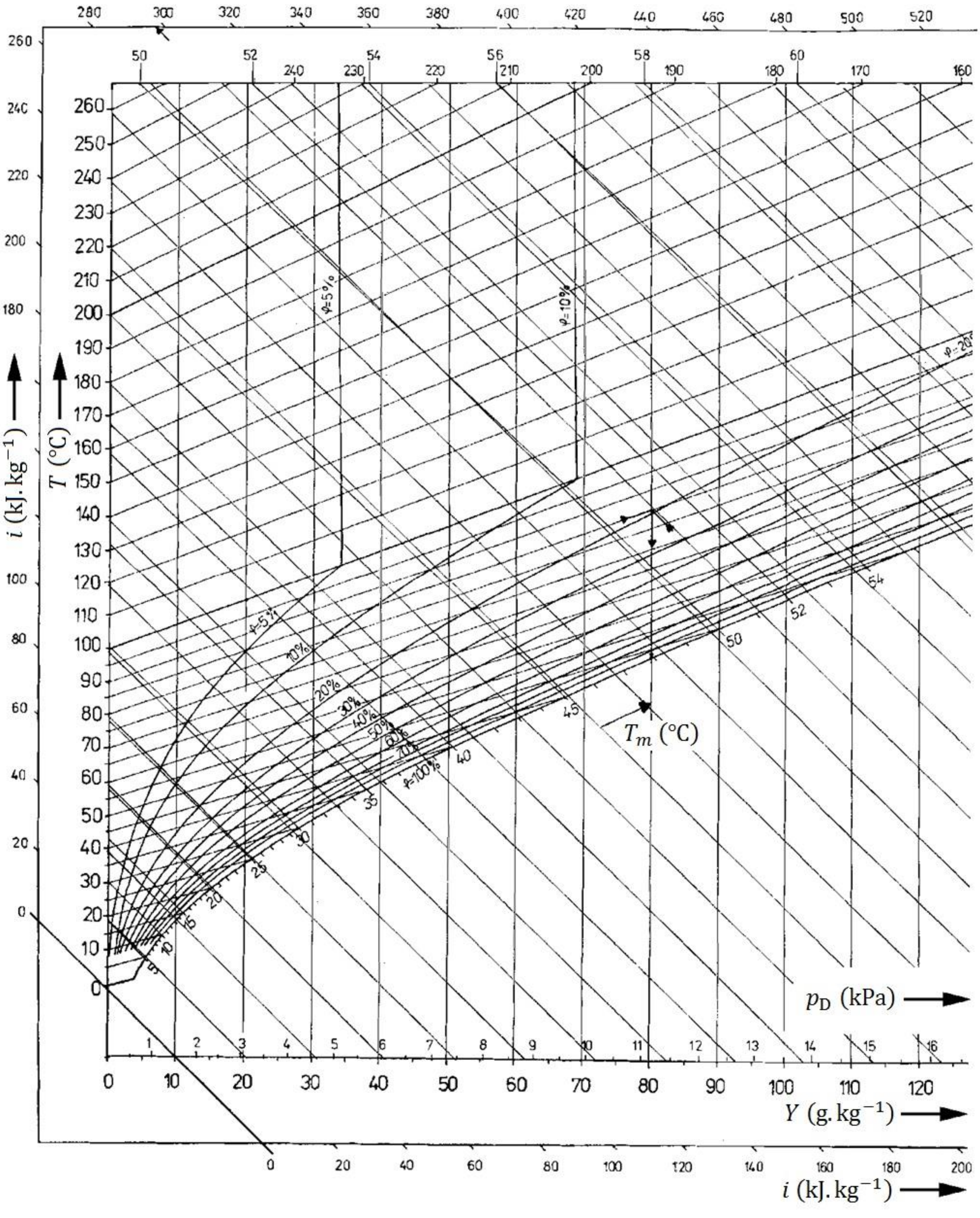


Fig. 4.1. i - Y diagram of moist air ($p_b = 9,8 \, . \, 10^4 \, Pa$) [9]

WET BODY

A wet body may be characterized as a system made up of a dry solid material (skeleton) and a fluid.
The ratio of the fluid to the absolutely dry material is expressed by the moisture u. Because an absolutely dry material exists only in exceptional situations, in drying we introduce the concept of dry matter m_S. The dry matter is determined by the unchanging value reached by a sample dried at an agreed temperature, most often $105\ °\mathrm{C}$. Heat sensitive materials are dried at a lower temperature, but the data must be supplemented by the temperature of drying. If the mass of the moisture is designated m_v, the moisture is expressed by the equation

$$u = \frac{m_v}{m_S} \tag{4.2}$$

For material whose dry matter is measured at $50\ °\mathrm{C}$, the moisture is expressed by the equation

$$u = \frac{m_v}{m_{S(50°\mathrm{C})}} \tag{4.3}$$

In addition to the moisture, the fluid content is expressed by the share of moisture determined by the ratio of the mass of the moisture m_v to the initial mass of the matter m_A. Such moisture is denoted as the moisture at entry into the dryer u_A and is expressed by the equation

$$u_A = \frac{m_v}{m_A} = \frac{m_v}{m_v + m_S} \tag{4.4}$$

MATERIAL AND ENERGY BALANCE OF A DRYER

In the drying process in a dryer, the heat transfer medium is in contact with the surface of the wet material, receives a certain amount of moisture from it and removes it from the dryer. The heat transfer media are mostly heated air and exhaust gases A diagram of a dryer is found in figure 4.2, with the inlet part marked as A, and the outlet, B.

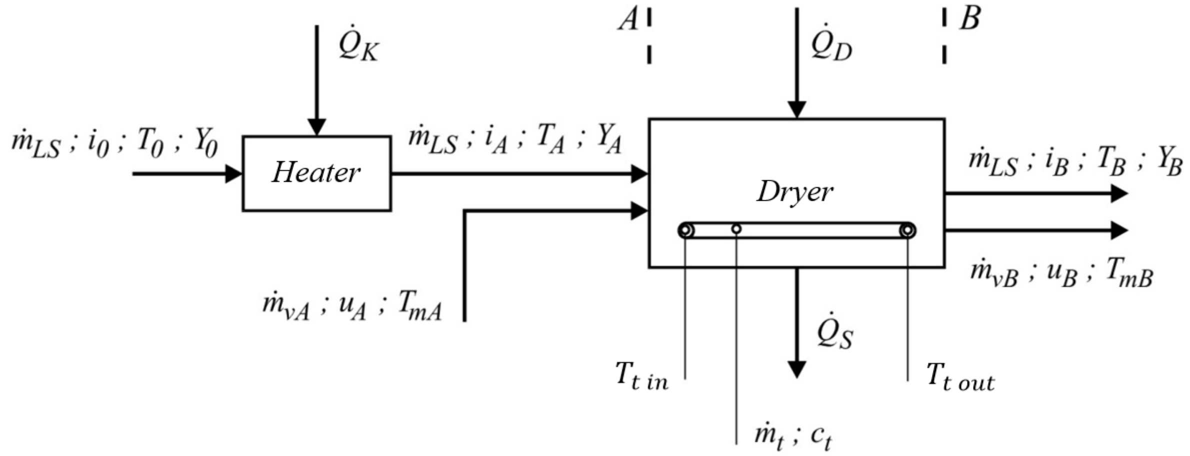


Fig. 4.2. Dryer diagram [9]

Overview of symbols in figure 4.2:

$\dot{m}_{LS}$	–	mass flow of dry air running through the dryer	$(\mathrm{kg.s^{-1}})$
i_0	–	enthalpy of air entering the heater	$(\mathrm{J.kg^{-1}})$
T_0	–	temperature of air entering the heater	(K)
Y_0	–	absolute moisture of air entering the heater	$(\mathrm{kg.kg^{-1}})$
i_A	–	enthalpy of air entering the dryer	$(\mathrm{J.kg^{-1}})$
T_A	–	temperature of air entering the dryer	(K)
Y_A	–	absolute moisture of air entering the dryer	$(\mathrm{kg.kg^{-1}})$
$\dot{m}_S$	–	mass flow of dry material (dry matter) in the dryer	$(\mathrm{kg.s^{-1}})$
u_A	–	moisture of the material on entry to the dryer	$(\mathrm{kg.kg^{-1}})$
u_B	–	moisture of the material on exit from the dryer	$(\mathrm{kg.kg^{-1}})$
T_{mA}	–	temperature of the material on entry to the dryer	(K)
T_{mB}	–	temperature of the material on exit from the dryer	(K)
$\dot{m}_t$	–	mass flow of devices transporting the material to be dried	$(\mathrm{kg.s^{-1}})$
c_S	–	specific heat capacity of the dry material (dry matter)	$(\mathrm{J.kg^{-1}K^{-1}})$
c_v	–	specific heat capacity of water	$(\mathrm{J.kg^{-1}K^{-1}})$
c_t	–	specific heat capacity of transport devices	$(\mathrm{J.kg^{-1}K^{-1}})$
$T_{t\,in}$	–	temperature of transport devices on entry	(K)
$T_{t\,out}$	–	temperature of transport devices on exit	(K)
$\dot{Q}$	–	total amount of heat consumed in drying	(W)
$\dot{Q}_K$	–	amount of heat consumed in heater	(W)
$\dot{Q}_D$	–	amount of heat brought directly into the dryer	(W)
$\dot{Q}_S$	–	heat loss from dryer to environment	(W)

The wet material enters the dryer at point A, it is moved in the dryer by a transport device, and leaves at point B. Cold air is blown by a fan at the heater, where it is heated from temperature T_0 to temperature T_A and moves into the dryer. On contact with the material, the air draws moisture from it, and leaves the dryer at temperature T_B. Sometimes the air is reheated, or all the heat necessary for drying is supplied directly in the dryer (in figure 4.2 marked as $\dot{Q}_D$).

In figure 4.2 is illustrated the basic process of drying, in which the heating fluid (heated air input) is used only once.

To determine the consumption of air and heat, a material and energy balance is created. In a constant state, moisture flow $\dot{m}_{vA} = \dot{m}_S\, u_A$ enters the dryer, and $\dot{m}_{vB} = \dot{m}_S\, u_B$ leaves the dryer, so the mass flow of the evaporated water is given by the equation

$$\dot{m}_v = \dot{m}_S\,(u_A - u_B) \tag{4.5}$$

Moisture $\dot{m}_{LA} = \dot{m}_{LS}\, Y_A$ comes into the dryer with the air, and $\dot{m}_{LB} = \dot{m}_{LS}\, Y_B$ leaves with the exit air, so the air moving through the dryer removes moisture as defined by the equation

$$\dot{m}_v = \dot{m}_{LS}\,(Y_B - Y_A) \tag{4.6}$$

A modified equation (4.6) gives the following:

$$\frac{\dot{m}_{LS}}{\dot{m}_v} = \frac{1}{Y_B - Y_A} = l \tag{4.7}$$

The letter l ($\mathrm{kg.kg^{-1}}$) in equation (4.7) designates the amount of air necessary to evaporate 1 kg of water, and is referred to as specific water consumption. In equation (4.7) the condition of air heating at constant moisture applies, and therefore $Y_A = Y_0$.

These heat flows enter and exit the dryer:

Table 4.1. Heat flows entering and exiting the dryer

ENTRY	heat flow (W)
With incoming cold air	$\dot{m}_{LS}\, i_0$
With moisture in the material	$\dot{m}_v\, c_v\, T_{mA}$
With dry material	$\dot{m}_S\, c_S\, T_{mA}$
With transport devices on entry	$\dot{m}_t\, c_t\, T_{t\,in}$
Heat flow introduced in the heater	$\dot{Q}_K$
Additional heat flow introduced directly in the dryer	$\dot{Q}_D$
EXIT	heat flows(W)
With exiting air	$\dot{m}_{LS}\, i_B$
With exiting dried material	$\dot{m}_S\, c_S\, T_{mB}$
With transport devices on exit	$\dot{m}_t\, c_t\, T_{t\,out}$
Losses to the environment	$\dot{Q}_S$

By comparing incoming and outgoing heat flows the following equation is obtained :

$$\begin{aligned} &\dot{m}_{LS}\, i_0 + \dot{m}_v\, c_v\, T_{mA} + \dot{m}_S\, c_S\, T_{mA} + \dot{m}_t\, c_t\, T_{t\,in} + \dot{Q}_K + \dot{Q}_D = \\ &= \dot{m}_{LS}\, i_B + \dot{m}_S\, c_S\, T_{mB} + \dot{m}_t\, c_t\, T_{t\,out} + \dot{Q}_S \end{aligned} \tag{4.8}$$

And its modification gives

$$\begin{aligned} \dot{Q} = \dot{Q}_K + \dot{Q}_D = \dot{m}_{LS}\,(i_B - i_0) + \dot{m}_S\, c_S\,(T_{mB} - T_{mA}) + \\ + \dot{m}_t\, c_t\,(T_{t\,in} - T_{t\,out}) + \dot{Q}_S - \dot{m}_v\, c_v\, T_{mA} \end{aligned} \tag{4.9}$$

Dividing the preceding equation by the mass flow of the evaporated water $\dot{m}_v$, there results the limit consumption of heat q ($\mathrm{J.kg^{-1}}$), equations(4.10) and (4.11).

$$q = \frac{\dot{Q}}{\dot{m}_v} = q_K + q_D = l\,(i_B - i_0) + q_m + q_t + q_S - c_v\, T_{mA} \tag{4.10}$$

$$q = \frac{i_B - i_0}{Y_B - Y_0} + \sum q_i - c_v\, T_{mA} \tag{4.11}$$

If the heat flow additionally brought into the drying chamber q_D and the initial enthalpy of the water evaporated from the material $c_v\,T_{mA}$ completely replace the heat loss from heating the dry material q_m in the transport devices q_t plus losses into the environment q_S, the equation below applies :

$$q_D + c_v\,T_{mA} = q_m + q_t + q_S \tag{4.12}$$

Such a dryer is called a theoretic dryer, and the enthalpy of the air in the dryer does not change : $i_A = i_B$. The process of drying for the theoretic dryer described on the i - Y diagram is shown in figure 4.3.

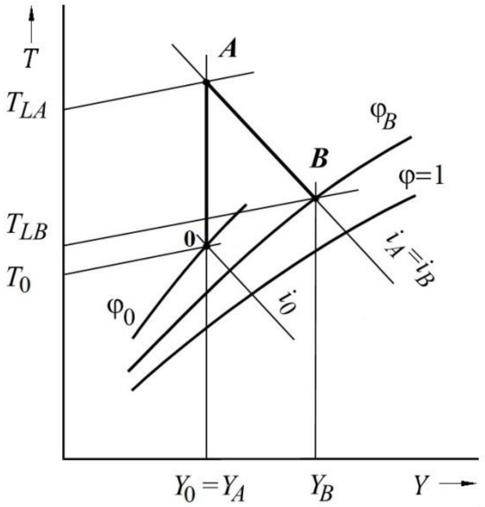


Fig. 4.3. Illustration of the process of drying for a theoretic dryer [9]

The theoretic dryer represents a special case of an *actual dryer* in which equation (4.12) does not apply. Equations (4.13) and (4.14) apply to it, with the expressions $\Delta < 0$ and $\Delta > 0$. Examples of the actual dryer described on the *i* - *Y* diagram are shown in figure 4.4.

$$\Delta = l\,(i_B - i_A) \tag{4.13}$$

$$\Delta = q_D + c_v\,T_{mA} - q_m - q_t - q_S \neq 0 \tag{4.14}$$

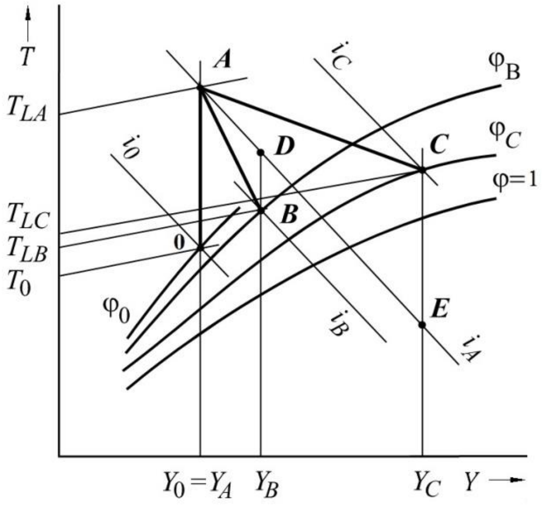


Fig. 4.4. Illustration of process of drying for $\Delta < 0$ and $\Delta > 0$ [9]

The case when $\Delta < 0$ is illustrated by the line $\overline{AB}$.From equation (4.13) is obtained

$$\Delta = l\ (i_B - i_A) < 0 \tag{4.15}$$

For $\Delta > 0$, the process of drying is illustrated by the line $\overline{AC}$ and there applies

$$\Delta = l\ (i_C - i_A) > 0 \tag{4.16}$$

From figure 4.4 it is noticeable that for $\Delta < 0$ and $\Delta > 0$ there are different limit air consumptions (equation (4.7)), and therefore different limit heat consumptions.

DRYING KINETICS

The basic task of the dynamic calculation of drying data is to establish the non-stationary fields of temperature and the moisture of the material in the course of drying. The dynamic of the drying process also serves to establish the necessary time of drying, together with the main dimensions of the dryer. The course of drying is influenced by a large number of factors, such as the natural properties of the material, the shape of the material, the initial and final content of moisture in the material and the critical content of the moisture. In evaluating the drying environment, we must take into account moisture, heat, speed, flow around the drying object, and the temperature difference on input and output. Further evaluations will consider the design of the dryer, equilibrium during drying, and many other factors.

Since many factors affect the course of drying and the dynamic calculation is very complex, we often make do with the basic dynamic dependence, which expresses the medium limit moisture of the material to be dried as a function of time, $\bar{u} = f(\tau)$, called the *drying curve*. In figure 4.5, the drying curve is illustrated in a general form, accompanied by the temperature of the material to be dried, in dependence on time.

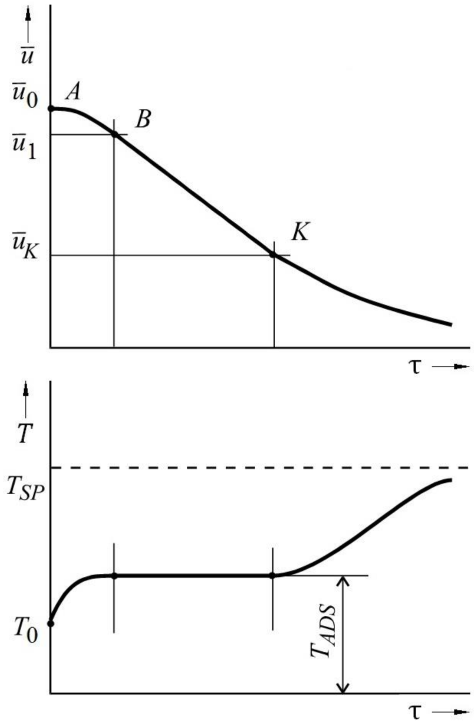


Fig. 4.5. Drying and temperature curve of dried body [9]

The drying curve can be divided into several parts. Between points A and B the moisture loss of the body increases over time as its temperature at a certain point rises from the initial temperature T_0 to the wet bulb temperature - also called *adiabatic saturation temperature*. The body moisture loss between points B and K is constant because the mechanism of moisture transfer from the body is the same as evaporation from the free water surface. After reaching point K, which we call the *critical point*, there is a significant change, the surface of the body is not sufficiently supplied with moisture and the moisture transfer is constantly slows down. Between points B and K the temperature of the body at the observed point does not change because the evaporation (phase transformation) takes place at a constant temperature. Beyond the critical point, the body temperature rises and approaches asymptotically the temperature of the drying medium T_{SP}.

The drying curve is determined by the dependence $\bar{u} = f(\tau)$ from the body mass as a function of time (4.2), while the other parameters are constant. These parameters can be the temperature of the drying medium, its humidity, medium speed, body dimensions and the like. If we measure the drying curves at several values of the same parameter, we get a set of curves expressing, for example, temperature effect. Such curves are necessary to determine the residence time of the material in the dryer.

The drying rate curve is frequently derived from the drying and temperature curve. The drying rate curve is understood as the change in the moisture of the material over time, i.e. the first derivation function $\bar{u} = f(\tau)$, (Fig. 4.6).

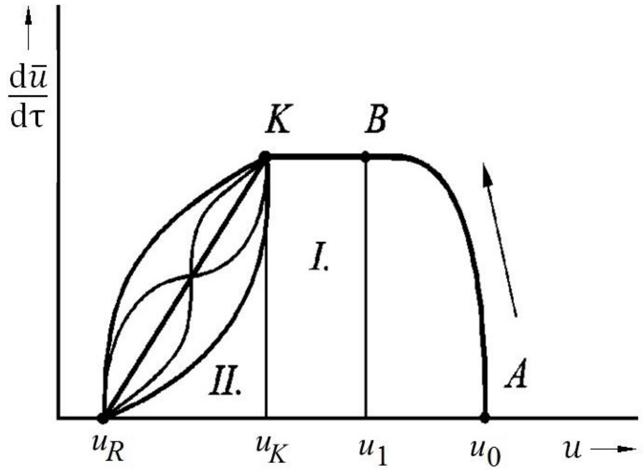


Fig. 4.6. Drying rate curve [9]

The curve between points A and B depicts the heating of the body to be dried, and the straight line between points B and K is called the *constant rate of drying* (designated I), the curve from point K depicts the *declining rate of drying* (designated II). The curves may have a variety of shapes in dependence on the relation of the moisture with the material´s properties. The process of drying finishes at *moisture equilibrium.* Every wet body may be dried only to its moisture equilibrium, which is dependent on the state of the environment (its temperature and relative moisture).

TYPES OF DRYERS

The design of a dryer takes into account the method of drying process. The rules according to which the operating parameters of drying are controlled (temperature, moisture, speed of drying environment, amount of material provided, speed of material movement, etc.) are referred to as *drying process* (*drying regime*).

Dryers are classified according to these aspects:

- *the type of drying medium* (air, exhaust gas, inert gas, steam),
- *the operating pressure of the drying environment* (atmospheric pressure, reduced pressure, increased pressure),
- *the method of providing heat to the dried material* (convection, radiation, conduction),
- *the flow of the drying medium around the material* (blowing, impact, flow, fluidization),
- *the nature of the operation*:
    - *parallel flow,*
    - *counter flow,*
    - *crossflow,*
- *the type of movement of the material to be dried in the dryer includes:*
    - *material to be dried is at rest* (tray dryer, drying cabinet, chamber dryer),
    - *source of movement is only its potential energy* (roller dryer, rotary dryer),
    - *source of movement is mainly the kinetic energy of the drying medium and the potential or kinetic energy of the material* (pneumatic dryer, fluidized bed dryer).

DRYING CABINET AND CHAMBER DRYER

These are in the class of periodic dryers (periodic operation) where the material to be dried is at rest on an immobile plate. Drying cabinets differ from chamber dryers only in terms of size. In figure 4.7 is depicted a chamber dryer in which various types of material may be dried. The heated air blown through the adjusting flaps from outside contacts the heat exchanger and flows around the drying material until the required moisture is attained. This system is used for smaller operations where continual operation of the dryer would not be economical.

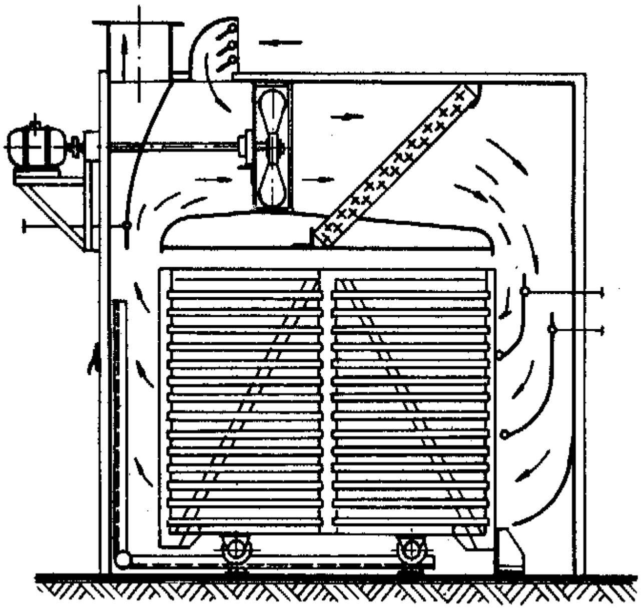


Fig. 4.7. Chamber dryer [9]

TUNNEL DRYER

Continually operating dryers are appropriate for large amounts of material of a similar type. Figure 4.8 illustrates a tunnel dryer. The material to be dried is brought into the dryer on carts and transported along the tunnel. Fresh air is blown in and heated by a heat exchanger. After a change in the direction of flow, the air flows counter-clockwise along the carts and removes moisture from the drying material. The used air leaves the dryer through the flaps and a certain part of the air is mixed with fresh air.

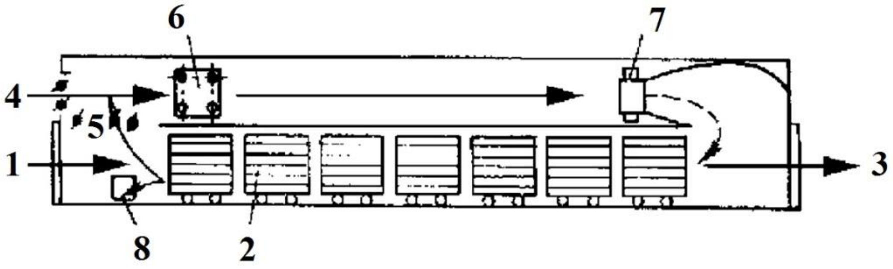


Fig. 4.8. Tunnel dryer [9]:
1 – entry of material to be dried, 2 – delivery cart, 3 – exit of dried material,
4 – entry of fresh air, 5 – flaps for setting the share of recirculating air,
6 – heat exchanger, 7 – fan, 8 – exit of air from dryer

MULTI-BELT DRYER

In multi-belt dryers the material passes through the chamber in such a way that at the end of the belt it is transferred to a further belt running in the opposite direction (Fig. 4.9). As a result, areas are progressively exposed to the drying medium. This gives a shorter drying time and increases the efficiency of the drying process.

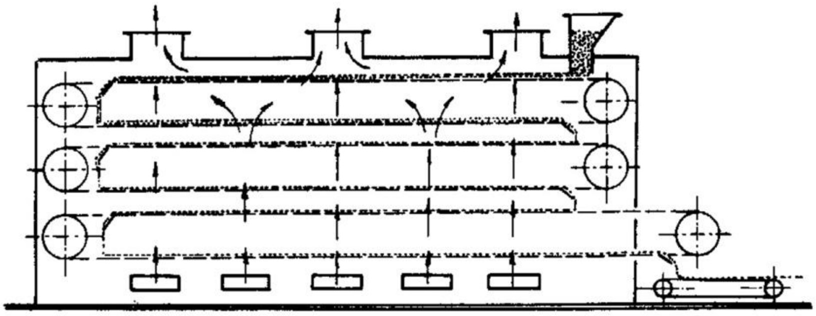


Fig. 4.9. Diagram of multi-belt dryer [9]

ROTARY TRAY DRYER

In a rotary tray dryer the material to be dried is placed on rotating trays made of perforated steel (Fig. 4.10). The material to be dried, is lifted, mixed by blades and moved into openings which are positioned alternately in the centre and on the perimeter of the individual trays, so that it gradually falls lower and lower towards the emptying screw. The drying air flows in horizontal levels across the material.

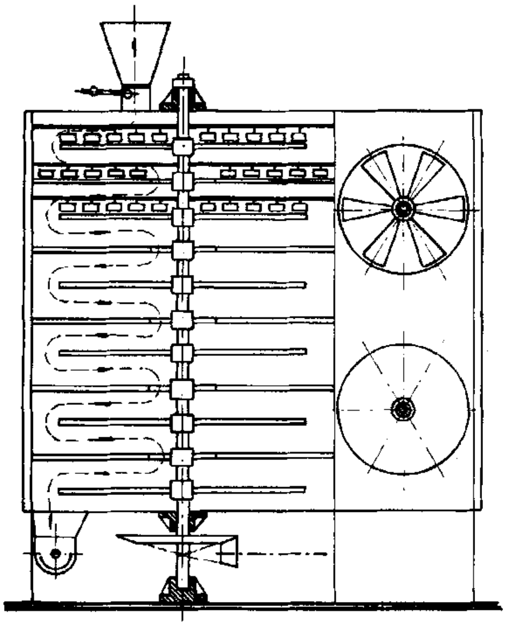


Fig. 4.10. Rotary tray dryer [9]

DRUM DRYER

The main part of a drum dryer is the cylindrical drum (Fig. 4.11 – position 1) with a slightly inclined axis placed on rollers. The drum rotates and is driven by an electric motor through a gearbox. The wet material is put into the drum at the upper level, and by rotation, the action of the drum mechanism and the flow of the drying medium, it progresses by complex movement to the exit point. The dried product falls into the collection chamber (Fig. 4.11 – position 2), and the drying medium is removed to a separator (Fig. 4.11 – position 3).

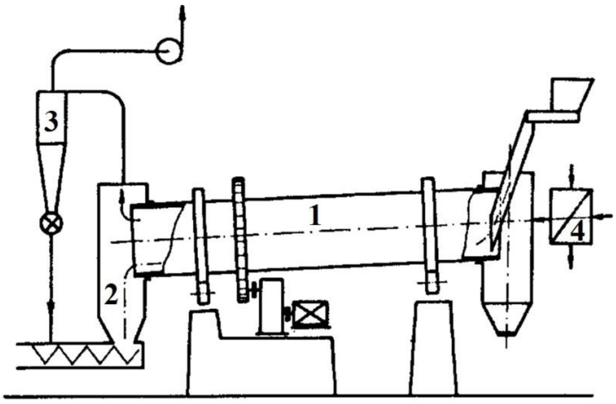


Fig. 4.11. Drum dryer [9]:
1 – cylindrical drum, 2 – chamber for dried product,
3 – separator, 4 – heat exchanger

Drums are welded from steel plate, and rotate at from 1 to 15 rpm. The drum's outer surface is insulated. A variety of internals (Fig. 4.12) are built into the drums for improving the heat transfer. The drying medium may be air, heated up in the heat exchanger (Fig. 4.11 – position 4), or exhaust gas. The outlet temperature of flue gas is about 800 °C and sometimes higher.

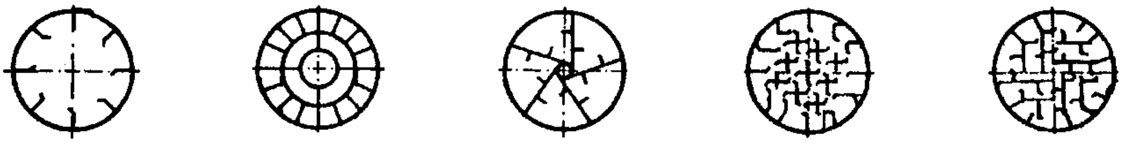


Fig. 4.12. Basic types of internals for drum dryers [9]

VACUUM DRYERS

In vacuum drying the amount of removed moisture is increased by reducing the total pressure per unit of time. The moisture in the dryer evaporates at the boiling point corresponding to the total pressure in the drying space; most industrial dryers working at low vacuum reach a pressure of about 600 Pa. In figure 4.13 it can be seen how the boiling point of water changes in dependence on the pressure. The basic diagram of the vacuum dryer can be seen in figure 4.14. The dryer is made up of these main parts: the dryer with heating system, the vacuum pump and the condenser.

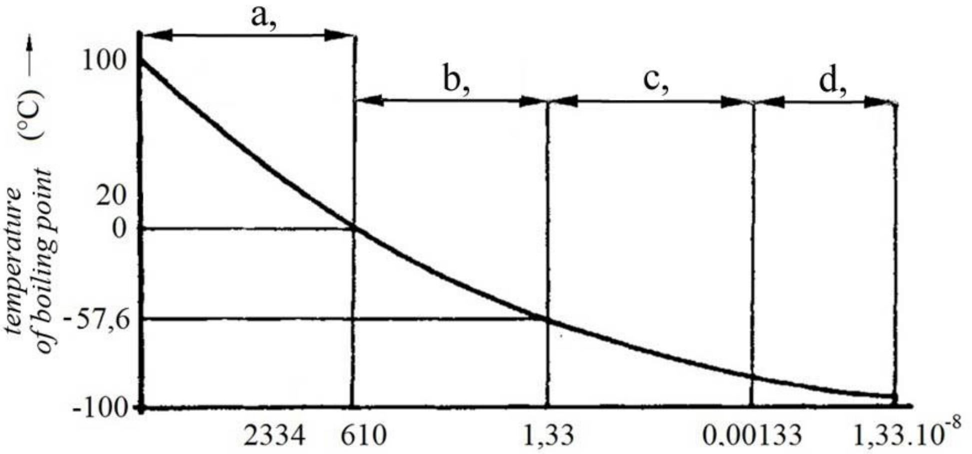


Fig. 4.13. Boiling point of water in dependence on pressure. (a – low vacuum, b – medium/rough/ vacuum, c – high vacuum, d – very high vacuum) [9]

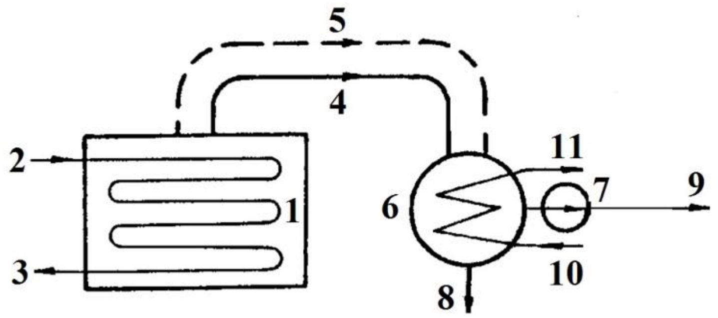


Fig. 4.14. Vacuum dryer [9]:
1 – dryer, 2 – inlet of steam, 3 – outlet of condensate, 4 – air with moisture,
5 – air, 6 – condenser, 7 – vacuum pump, 8 – inlet of condensed moisture,
9 – outlet of air, 10 – inlet of cooling water, 11 – outlet of cooling water

Heat is brought into the drying space by conduction or radiation, where the material to be dried is located. Water vapour (or another material) is brought into the condenser, where it is condensed by the cooling water. The drying chamber, condenser and connecting tube space are connected to the vacuum pump, which maintains the lower pressure and sucks out the moisture and air that has leaked into the system. This type of dryer works most often in discontinuous mode (only exceptionally as a continuous dryer).

DRYING CABINET WITH AUXILIARY HEATER

With longitudinal layer blowing, the material to be dried is generally in contact with the drying environment at the top, and only sometimes at the bottom . However, if the drying medium passes through the material on a permeable tray (perforated metal, wire mesh and the like), enhanced mutual contact occurs and consequently the speed of drying is significantly increased.

A dryer with blow-through layers is used for drying granular materials or small particles with low bulk densities (grains, in particular hops, hay etc.), with the particles not moving on the tray.

In figure 4.15 is depicted a discontinuous dryer with blow-through layers, where the share of circulating fresh air can be regulated. The drying air is heated in a heat exchanger and, after travelling through the material to be dried, is in part expelled and in part recirculated.

A dryer with blow-through layers may also be continuous. These are essentially belt dryers in which the belt is blow-through – for example the belt is a wire mesh (Fig. 4.9).

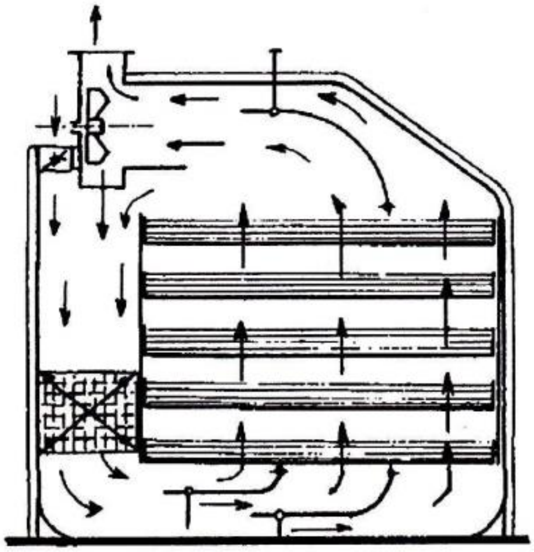


Fig. 4.15. Diagram of a dryer with blow-through layers [9]

FLUID DRYER

With fluid drying, the granular material in the dryer creates a layer which is kept in a fluid state by an aerodynamic flow effect in the drying environment.

Fluid dryers can be *periodic*, with the material fed in in a batch and removed from the dryer at the end of the process. The use of periodically working dryers has expanded quite extensively in operations where the type of material to be dried changes frequently (pharmaceutics, various chemical operations) and where, due to the batch character of production, the use of a continuous fluid dryer is not economically appropriate. The intensity of the drying process in fluid dryers working periodically is several times higher than in chamber dryers with longitudinal blowing.

Continuous dryers have been successfully integrated into production lines because the high intensity of the drying process achieved reduces drying time to correspond to that of the other technological operations on a continuous production line.

The basic makeup of fluid dryers, as regards the method of inputting and removing material and the drying environment, is presented in figure 4.16.

Figure 4.16*a* shows intake above the material to be dried and removal just above the rack; in figure 4.16*b* it is the reverse. For treating wet material, the equipment most often used includes worm, plate, chamber, vibration or pneumatic feeders, and removal is most frequently carried out by regulated overflow, sometimes also by worm or chamber feeders.

The method shown in figure 4.16c differs from the preceding ones in that the feeding and removal both take place above the layer. For the sake of even drying, this system is used only in large fluid dryers where the danger of a 'shortcut' (when the input material leaves the dryer by the shortest route) is small. This is similar to the case in figure 4.16*d*, where the dried material is discharged by means of an overflow pipe. This method is most often used in multi-stage fluid dryers, in which the stages are set one above the other. The set-up according to figure 4.16*e* is used in dryers with smaller flow velocity in the drying environment than the fluidization threshold speed. The material rippled through the medium advances along the inclined grate to the exit point. A speed lower than the limit fluidization speed is also used in the arrangement shown in figure 4.16*f*, where the material advances along the grate due to the influence of the rippling of the layer throughout the drying environment, as well as by the influence of the vibration movement of the grate.

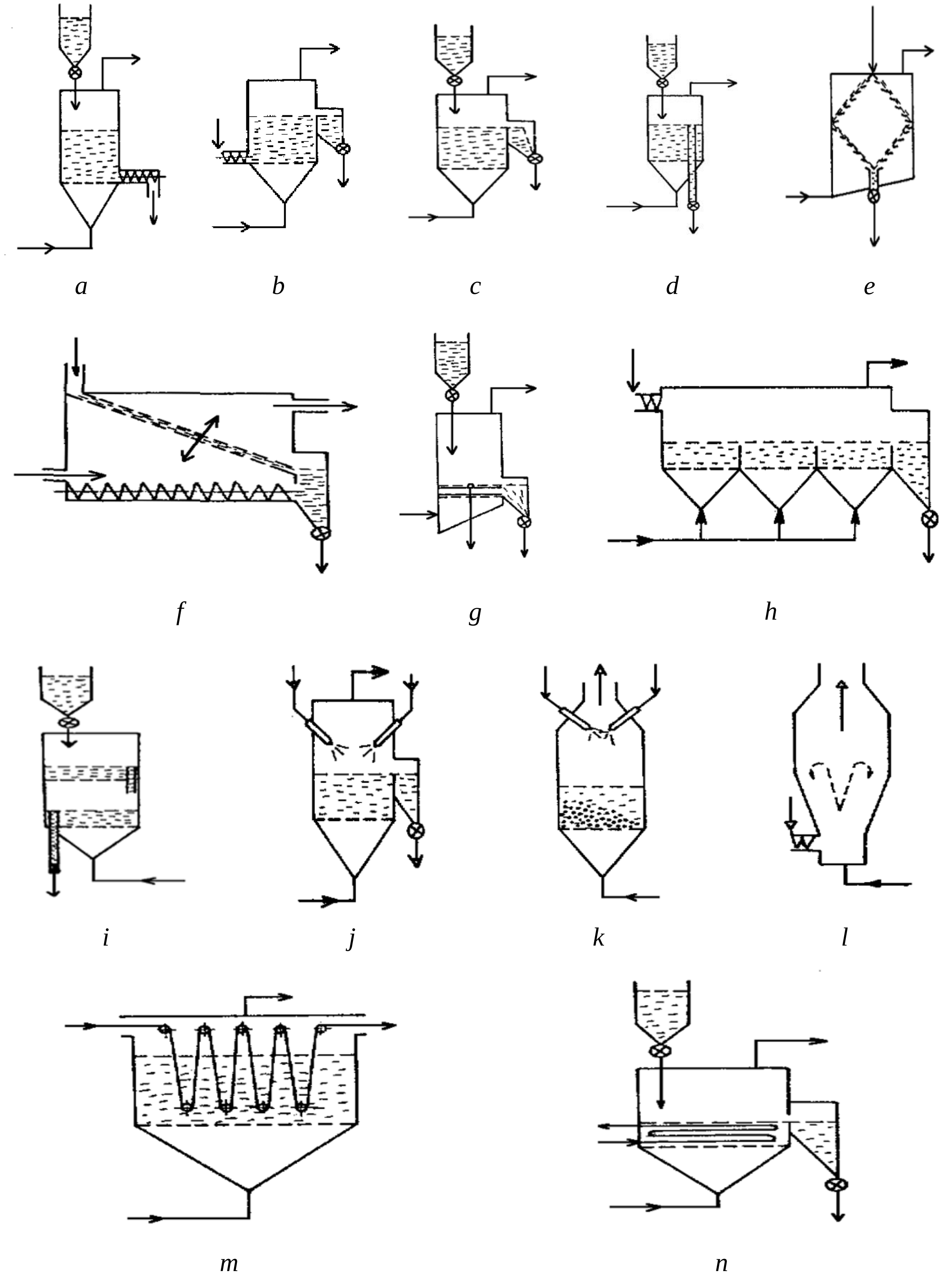


Fig. 4.16. Basic arrangements of fluid dryers [9]:
a – n description in the text

The equipment in figure 4.16*h* and figure 4.16*i* are multistage, with the stages arranged above (4.16*i*) or one behind the other. In multistage devices, other technological processes, such as cooling, spraying, distributing and the like, are carried out together with the drying.

The equipment in figure 4.16*j* and figure 4.16*k* also makes it possible to use fluid drying for solutions, suspensions, pastes, etc.. In these cases, the material is sprayed by nozzles (pasty materials, for example, with a special vibratory feeder delivering them in the form of threads) either above the fluid layer or into a layer formed by keeping the material longer in the device. If the material particles have a tendency to stick (coagulation) a layer of inert material is included (glass, siliceous sand, etc.).

In figure 4.16*g* is shown mechanical rippling of the fluid layer; the material is fed onto the grate from above and the rippling is brought about by blowing the layer through the environment and by mechanical mixers rotating above the grate.

The example in figure 4.16*l* is a grateless fluid dryer in which the moist material is carried by the flow of the drying environment to a device whose dimensions expand so that larger or clumpy particles fall out of the flow as a result of reduced flow speed. They end up in places where the flow speed is sufficient for the flow environment to pick them up again. Accordingly, the clumpy material in the device is jetted upwards and dried. The clumpy particles are thus broken up until the now-dried particles of the material can exit the device. This type of dryer is called a *jet* dryer.

Another example in figure 4.16*m* shows drying by continuous belts in the fluid layer. In this case, the fluid layer of inert material intensifies the entry of heat from the drying environment to the material belt (textile, paper and similar). The evaporated moisture is carried out of the equipment by the drying media.

The final example in figure 4.16*n* is used when the amount of drying medium necessary to achieve a fluid state is not sufficient for removing moisture. Additional heating areas situated in the fluid layer ensure the course of the drying process at a constant temperature instead of the usual adiabatic style.

VIBRO-FLUID DRYER

A vibro-fluid layer represents a combination of mechanical and aerodynamic rippling of the layer, and so takes advantage of both methods to achieve homogenous layers along with a restriction of the intensity of the process from the speed of flow of the gas medium . In heat and diffusion processes, , after a so-called *pseudo-fluid state* has been achieved, the vibration motion of the grate leads to intensive mixing of the particles along the cross-section of the layer. This allows good contact of the material with the heat-exchange areas or with the flow medium .

The principle of the device is illustrated in figure 4.17*a,* with the particles situated on an impermeable grate. The grate is mounted on springs and is moved up and down by means of an ‘exciter’. If the speed of the grate and the particles is less than gravitational acceleration, the particles do not separate from the grate. If, however, the grate and the particles are made to speed up by means of the exciter, the particles separate as the grate travels upwards and then again fall onto the grate during the downward movement.

The particle movement method described is called the *vibro-fluid layer of dense particles on an impermeable grate*. If this principle is used in drying, the particles are blown in a drying environment parallel to the grate.

In 4.17*b* is shown the working principle of the device, which operates by ripple vibration and at the same time by a fluid layer. In this case, the particles separate from the grate by the action of the mechanical element (by the exciter) and the aeromechanical element (by the air blown through the grate). The vibratory motion contributes to the intensification of the heat and mass transfer, especially in the area where the air flow speed w_0 is lower than the limit speed of fluidization. This case is referred to as the *vibro-fluid layer of dense particles on a permeable grate*.

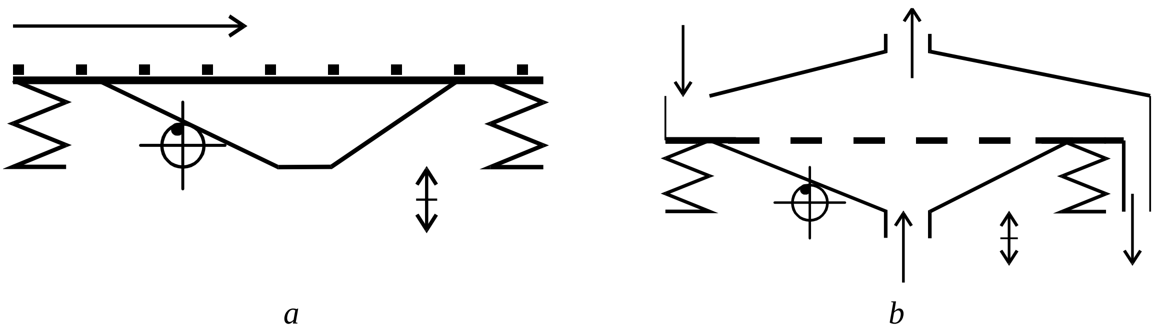


Fig. 4.17. Principle of operation of a vibro-fluid device [9]:
a – b description in the text

The *vibro-fluid channel* shown in figure 4.18 works on this principle and, besides drying, handles many other processes (heating, cooling, roasting, granulation and more).

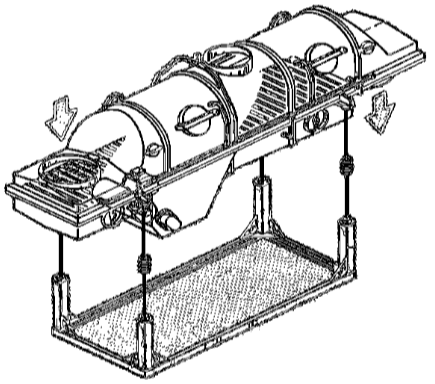


Fig. 4.18. Vibro-fluid channel [9]

SPRAY DRYER

Drying by spraying can be defined as the drying of a lightly dispersed solution, emulsion or suspension in an environment of warm air, heated steam, inert gas or an exhaust gas mixture together with air under conditions that allow the dried product to be retrieved in the form of a fine powder. By gentle dispersion a large surface is achieved, rapid evaporation occurs, the drying process takes place at a relatively low temperature (in the initial drying stage usually from 35 to 55 °C), and only in the final stage does the drying temperature of the particles rise. The particles of the material to be dried under such conditions are only briefly exposed to the action of higher temperatures, which is an advantage for all heat-sensitive materials or for materials that oxidize easily. For these reasons spray dryers are common in the chemical and food industries, where they are used for the drying of milk, eggs, egg whites, fruit juices, detergents, yeasts, coffee and tea extracts, among others.
Figure 4.19 is a diagram of a spray dryer.

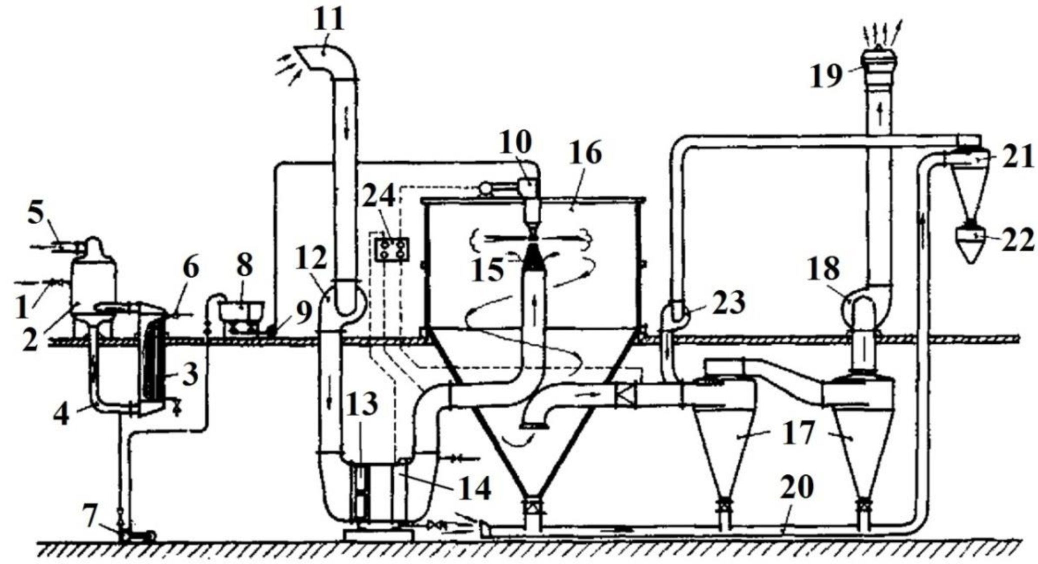


Fig. 4.19. Spray dryer [9]:
1 – intake valve, 2 – vacuum chamber, 3 – heat exchanger, 4 – pipe, 5 – pipe, 6 – steam intake, 7 – pump, 8 – distributor tank, 9 – pump, 10 – sprayer, 11 – air intake, 12 – ventilator, 13 – filter, 14 – heat exchanger, 15 – distributor, 16 – drying chamber, 17 – cyclone, 18 – fan, 19 – filter, 20 – pneumatic feeder, 21 – cyclones, 22 – dried product separator, 23 – ventilator, 24 – control panel

The line is made up of equipment for the preparation and heating of the material to be dried, the drying chamber with the spraying equipment, the feeding equipment, the dusting device and the exhaust fan for the drying environment. The drying medium is most often air or diluted exhaust gases. The drying material is brought to the dusting device by the feeder pump, which may be a gear, single-pump, piston or similar item. The main prerequisite is a continuous, uninterrupted supply of the material to the spraying equipment.

The drying chamber is most frequently of cylindrical shape with a vertical axis and a flat or conical bottom. The walls of the drying chamber are of steel plate, tiling, concrete or the like. The inner surface of the chamber must be smooth and without protrusions, so that the powder in the chamber does no clump or over-heat. Accordingly, drying chambers typically have good heat insulation. In the upper or lower part of the chamber is the dispersing device (nozzle or spraying disc). The dried powder falls to the base of the drying chamber and is removed mechanically or pneumatically. The dried matter passes from the drying chamber to the dusting device, consisting of either cyclones or a fabric sleeve filter, sometimes a wet filter (washer). The fan is usually located behind the dusting device, so the chamber works as a vacuum.
The task of the dispersion equipment is to break the dried material into small particles. Thus a significantly large surface of the dried material is created, which is the condition for rapid drying. In industrial dryers, droplets of a size from 50 to 300 μm are most frequent.

In dispersion it is necessary to overcome these forces that hold fluids together:

- surface tension, which occurs as a tendency to hold the particles together so that they occupy a minimal volume,
- viscosity,
- inertia forces appearing with the change of speed.

Current dryer designs feature three basic methods of dispersion:

- mechanical, solid nozzles making use of higher pressures,
- pneumatic, two-fluid nozzles with compressed air,
- centrifugal, rotating nozzles (spraying discs).

Mechanical spraying (Fig. 4.20) although the oldest technique, is used due to its many advantages. The fluid supplied to the spray nozzle under pressures of 3 to 7 MPa enters the spraying chamber tangentially, thus achieving a distinct swirling motion that is maintained even after leaving the chamber. The material initially forms a film in the shape of a conical area which, under pressure, breaks down into individual droplets.

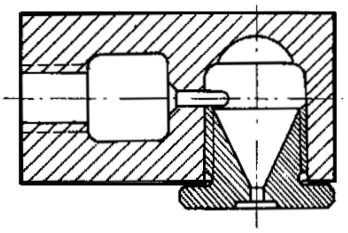


Fig. 4.20. Mechanical sprayer [9]

Pneumatic sprayer (Fig. 4.21) with two-fluid nozzles spraying liquid using a gas medium. Due to the rapid flow of air (100 to $200\ \mathrm{m.s^{-1}}$) it leads to the forming of a misty aerosol.

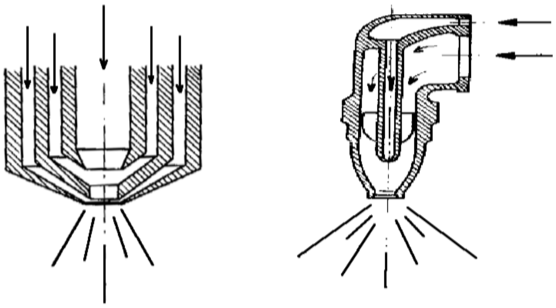


Fig. 4.21. Pneumatic sprayer [9]

With *centrifugal spraying* (Fig. 4.22) the fluid drips freely onto a disc of various designs rotating at high speed. The role of the spray disc is not only to disperse the fluid forcefully and equally, but also to form a suitable cloud that will mix well with the air. The disc speed ranges from 100 to $200\ \mathrm{m.s^{-1}}$ which, with different diameter discs, corresponds to a rotational frequency of from 4000 to $40\,000\ \mathrm{min^{-1}}$. The discs are mostly driven by an electro-motor via belts or pinions .

The high intensity of drying in spray dryers results in a short stay for the particles in the drying chamber (several seconds).

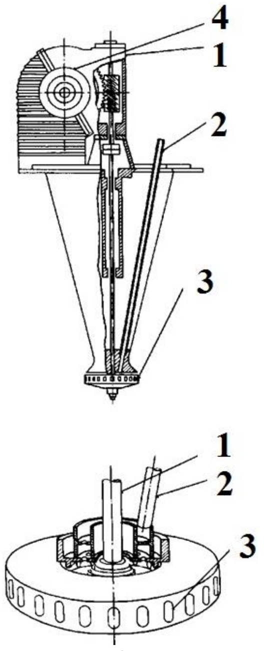


Fig. 4.22 Centrifugal sprayer [9]:
1 –driving shaft, 2 – fluid intake, 3 – spray disc,
4 – disc drive (motor with gearbox)

Rising energy prices, constant demand for high-quality finished product, the expanding range of products manufactured by spray drying, and also tighter requirements for the protection of the environment are pushing drying equipment manufacturers to develop new technologies and new types of devices. As such can be considered:

- equipment for recuperating heat from the heat escaping from a spray dryer made up of one or more heat exchangers. Exchangers working at temperatures above the dew point of exhaust air (above the saturation curve) are used, as well as exchangers partially condensing water vapour;
- a combination of a spray dryer with a fluid bed at the bottom of the chamber to solve the problem of stickiness of the product;
- two-stage drying, a combination of spray and vibro-fluid drying. The line allows for the deliberate separation of the drying and the cooling processes into several sections, thus gaining an increase in quality indicators along with a reduction in the consumption of heat energy in the drying process.

In figure 4.23 is a diagram of a recuperation system for a spray dryer using heat from moist air without a phase change, for usage with dairy products. The air leaving the spray dryer, which reaches a temperature of 100 °C and more, and whose relative moisture is often less than 20 %, enters a tube heat exchanger to heat the water. The water from the tube exchanger is reheated in another (plate) exchanger with fresh air, which is heated up by steam or gas to the temperature necessary for entry into a dryer in another device.

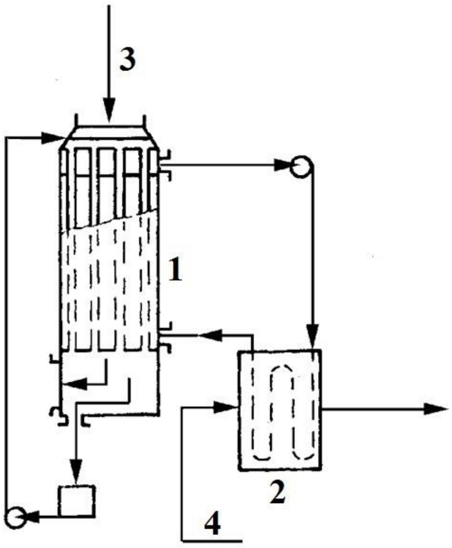


Fig. 4.23 Diagram of a recuperation system for a spray dryer [9]:
1 – tube exchanger, 2 – plate exchanger, 3 – air from dryer, 4 – fresh air

A combination spray dryer with a fluid bed is shown in figure 4.24. The arrangement is called a FSD (Fluidized Spray Dryer) and is produced by the Niro Atomizer Company.

The drying chamber differs from a normal spray dryer mostly in:

- the very short cylindrical part,
- the slender cone part,
- the bottom part of the cone finishing with the fluidization device,
- the drying medium entering into the upper part of the chamber and exiting from the upper part, together with the dried material, to the separating device,
- having in the bottom part of the chamber an independent inlet for air to the fluidization device.

The result of such an assemblage is that under the influence of the strong effect of the fluid bed, higher moisture and a share of fine recycled material occur in the arrangement of the particles. This solves the problem of product stickiness. This system increases the thermal efficiency of the process, since it allows the drying media to operate at high input and low output temperatures and at low product temperature.

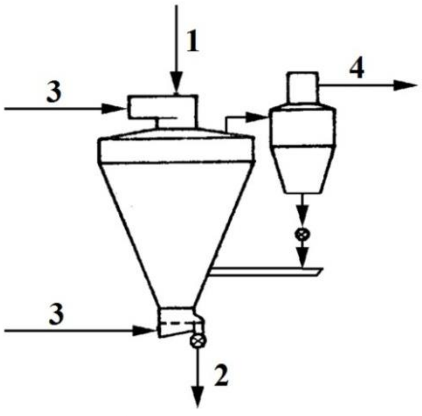


Fig. 4.24 Diagram of spray dryer with fluidization. [9]:
1 – filling, 2 – product, 3 – drying air, 4 – escaping gas

In figure 4.25 is a diagram of a two-stage dryer consisting of a spray dryer /2/ vibro-fluid drying equipment /6/ and vibro-fluid cooling equipment /7/. This configuration is mostly used for processing milk, since it ensures good resultant dissolubility and dispersibility. By a suitable modification, the line can also be used as an 'instantizer'.

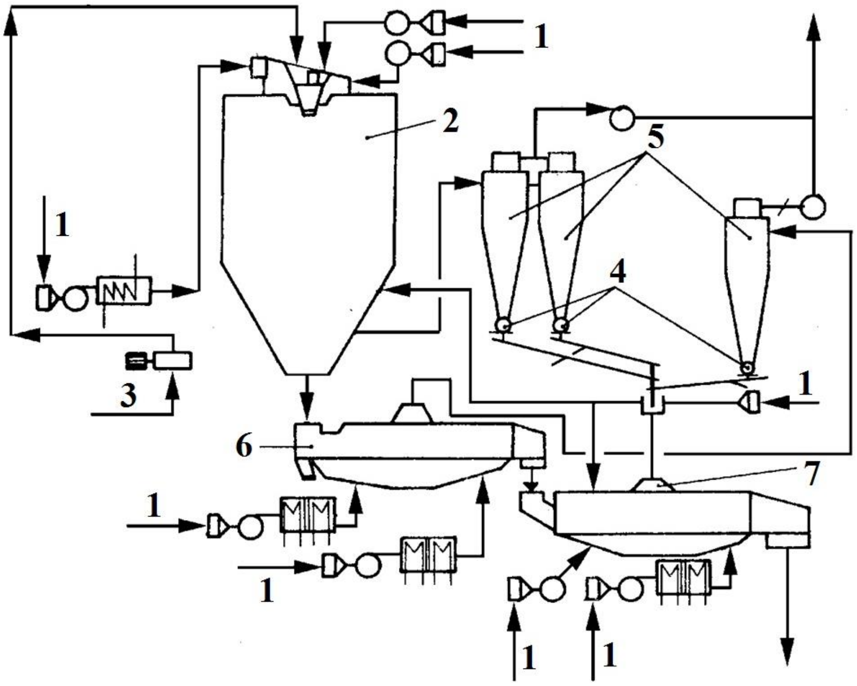


Fig. 4.25 Diagram of two-stage drying [9]:
1 – input of cold air, 2 – spray dryer, 3 – input of product to be dried,
4 – dried product, 5 – separation cyclones, 6 – vibro-fluid drying equipment,
7 – vibro-fluid cooling equipment

LIST OF SYMBOLS

c_{pv}	–	average air heat	$(\mathrm{J.kg^{-1}K^{-1}})$
c_{pvp}	–	average steam heat	$(\mathrm{J.kg^{-1}K^{-1}})$
c_t	–	specific heat capacity of transport devices	$(\mathrm{J.kg^{-1}K^{-1}})$
c_v	–	specific heat capacity of water	$(\mathrm{J.kg^{-1}K^{-1}})$
c_S	–	specific heat capacity of dried material (dry matter)	$(\mathrm{J.kg^{-1}K^{-1}})$
i	–	enthalpy of moist air	$(\mathrm{J.kg^{-1}})$
i_A	–	enthalpy of air entering dryer	$(\mathrm{J.kg^{-1}})$
i_B	–	enthalpy of air leaving dryer	$(\mathrm{J.kg^{-1}})$
i_0	–	enthalpy of air entering calorifier	$(\mathrm{J.kg^{-1}})$
l	–	average air consumption	$(\mathrm{kg.kg^{-1}})$
m_v	–	mass of fluid in moist body	(kg)
m_A	–	initial weight of material	(kg)
m_S	–	mass of dry matter	(kg)
$m_{S(50°\mathrm{C})}$	–	mass of dry matter at $50\ °\mathrm{C}$	(kg)
$\dot{m}_t$	–	mass flow of devices delivering material to be dried	$(\mathrm{kg.s^{-1}})$
$\dot{m}_v$	–	mass flow of evaporated water in dryer	$(\mathrm{kg.s^{-1}})$
$\dot{m}_{LS}$	–	mass flow of dry air going through dryer	$(\mathrm{kg.s^{-1}})$

$\dot{m}_S$ – mass flow of dried material (dry matter) through dryer $(\mathrm{kg.\,s^{-1}})$
q – average consumption of heat $(\mathrm{J.\,kg^{-1}})$
q_m – average consumption of heat in material $(\mathrm{J.\,kg^{-1}})$
q_t – average consumption of heat in transport device $(\mathrm{J.\,kg^{-1}})$
q_D – average consumption of heat fed directly into dryer $(\mathrm{J.\,kg^{-1}})$
q_K – average consumption of heat consumed in calorifier $(\mathrm{J.\,kg^{-1}})$
q_S – average consumption of heat in form of losses to surroundings $(\mathrm{J.\,kg^{-1}})$
r_0 – evaporating heat of water at temperature $0\ ^\circ\mathrm{C}$ $(\mathrm{J.\,kg^{-1}})$
u – average moisture $(\mathrm{kg.\,kg^{-1}})$
u_A – average moisture of material on entry to dryer $(\mathrm{kg.\,kg^{-1}})$
u_B – average moisture material of material on exit from dryer $(\mathrm{kg.\,kg^{-1}})$
$\bar{u}$ – average moisture $(\mathrm{kg.\,kg^{-1}})$
$\dot{Q}$ – total amount of heat consumed in drying (W)
$\dot{Q}_D$ – amount of heat fed directly into dryer (W)
$\dot{Q}_K$ – amount of heat consumed in heater (W)
$\dot{Q}_S$ – losses of heat from dryer to surroundings (W)
T – temperature of air (K)
T_m – wet bulb temperature (K)
T_{mA} – temperature of material on entry to dryer (K)
T_{mB} – temperature of material on exit from dryer (K)
$T_{t\ in}$ – temperature of transport devices at entry (K)
$T_{t\ out}$ – temperature of transport devices at exit (K)
T_A – temperature of air entering dryer (K)
T_0 – temperature of air entering calorifier (K)
Y – contents of water vapor in 1 kg of dry air $(\mathrm{kg.\,kg^{-1}})$
Y_A – absolute moisture of air entering dryer $(\mathrm{kg.\,kg^{-1}})$
Y_0 – absolute moisture of air entering calorifier $(\mathrm{kg.\,kg^{-1}})$
Δ – difference of average consumption of heat between actual dryer and theoretic dryer $(\mathrm{J.\,kg^{-1}})$
φ – relative moisture (1)
τ – drying period (s)

5 COOLING EQUIPMENT

Cooling technology is a complex area that has a significant impact on solutions to mankind's essential problems.

One considerable problem is preserving the quality of foods, which has been satisfactorily resolved for about one-third of the inhabitants of the planet. Of the amount of foodstuffs produced annually around the world, a significant part becomes waste. Although cooling technologies are employed in almost all industrial sectors, they have their greatest contribution in the food sector, where they enable the population to be supplied with food products by overcoming fluctuations caused by their seasonal character.
However, cooling equipment can also be utilised in the chemical, metallurgical, and construction industries, in winter sports, air-conditioning, product testing, biology and medicine. Progress in cryogenics has greatly influenced metallurgical production, electro-technology and many other scientific areas. The idea of using the heat derived from coolers, today known as heat pumping, has been developing since 1927. The aim of cooling is to remove the heat from objects or materials which will thus be cooled to temperatures lower than their surroundings, either changing their state or removing their reaction heat. Removing heat from a cooling matter may occur by direct cooling, or indirect cooling employing at least one medium or a circulating heat transfer medium which transfers heat from the cooling medium to the refrigerant without changing its state.

Refrigerant is a medium that within the cooling circuit receives heat under low pressure and temperature and distributes it at higher pressure and temperature. The inflow and outflow of heat (apart from the circulation of gases) are connected with a change of phase of the refrigerant (evaporation with the inflow of heat and condensation in its distribution).
Those media mostly used as refrigerants are: water, ammonia, carbon dioxide, hydrocarbons (methane, ethane, propane, ethylene, propylene), and halogenated hydrocarbons. From the last mentioned, the best-known is dichlorodifluoromethane, also known as freon.
Refrigerants are subject to many requirements, which can be briefly formulated as:

- heat properties,
- physical properties,
- chemical properties (flammability, explosiveness, impact on construction materials),
- physiological effects on the human organism,
- price.

Although they fulfill the required properties well, the use of halogenated hydrocarbons is on the decline at the present time since they are a significant factor in the destruction of the protective ozone layer around the earth.

Cooling circulation is created by a sequence of individual processes, after which the working medium (refrigerant) returns to its initial state. Circulation is carried out in a set of machines and equipment attached by tubes called a cooling circuit.

STEAM CIRCULATION

With steam circulation, the cooling effect is achieved by the evaporation of the refrigerant. A mechanically-driven compressor is used for creating the desired pressure in evaporation and for compressing the refrigerant. Figure 5.1 is a diagram of a steam circuit made up of an evaporator, compressor, condenser and a throttle unit.

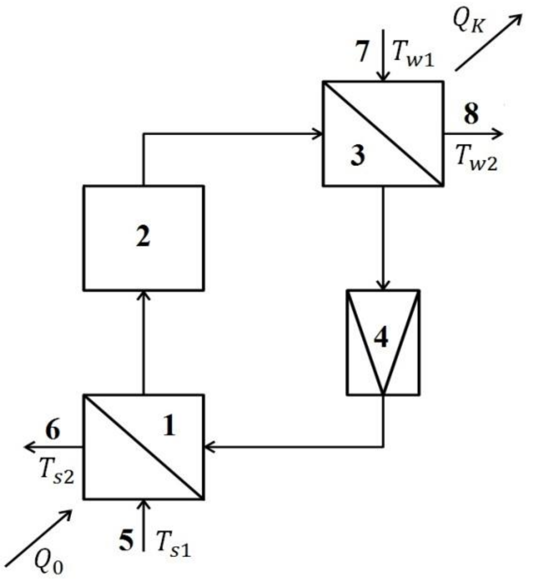


Fig. 5.1. Diagram of a steam circuit [9]:
1 – evaporator, 2 – compressor, 3 – condenser, 4 – throttle unit, 5 – inflow of cooled medium, 6 – outflow of cooled medium, 7 – inflow of cooling medium,
8 – outflow of cooling medium

With the inflow of heat Q_0 to the evaporator, the refrigerant evaporates and is sucked into the compressor. The evaporator is a heat exchanger in which, if the goal is to reach the desired temperature of the cooled medium for exit T_{s2} (Fig. 5.2), the evaporation temperature T_0 must be lower by the difference of temperatures δ_2 necessary for the transfer of the heat.

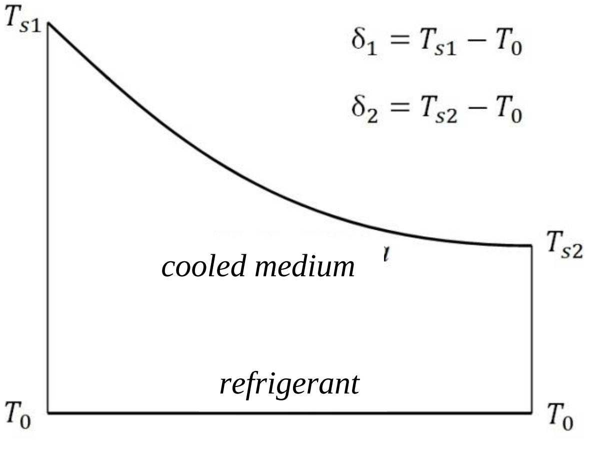


Fig. 5.2. Diagram of the course of temperatures in an evaporator [9]

After the compression of steam, the refrigerant passes through it to the condenser, where the heat Q_K is removed by the cooling medium, in other words, condensed. The condenser is a heat exchanger in which the exit heat of the cooling (heating) medium determines the amount (and so also the pressure) of the condensation heat T_{w2} and the difference of the temperatures

δ_2 (Fig. 5.3) that is necessary in the given heat-exchange area for the heat Q_K to move from the refrigerant to the cooling medium.

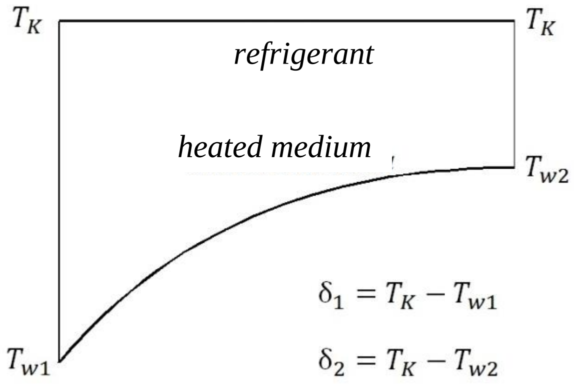


Fig. 5.3 Diagram of the course of temperatures in a condenser [9]

The liquid refrigerant from the condenser passes to the throttle unit, where its pressure is throttled and the liquid changes into wet steam. The throttle unit is usually a valve or a capillary pipe.

ABSORPTION CIRCUIT

Its basic principle is the replacement of compression by a heat process in which the refrigerant under low pressure is absorbed by a suitable medium (absorbent) (Fig 5.4), and then the solution is transported to the heater (desorber) where it is freed (desorbed) by the flow of heat from the solution.

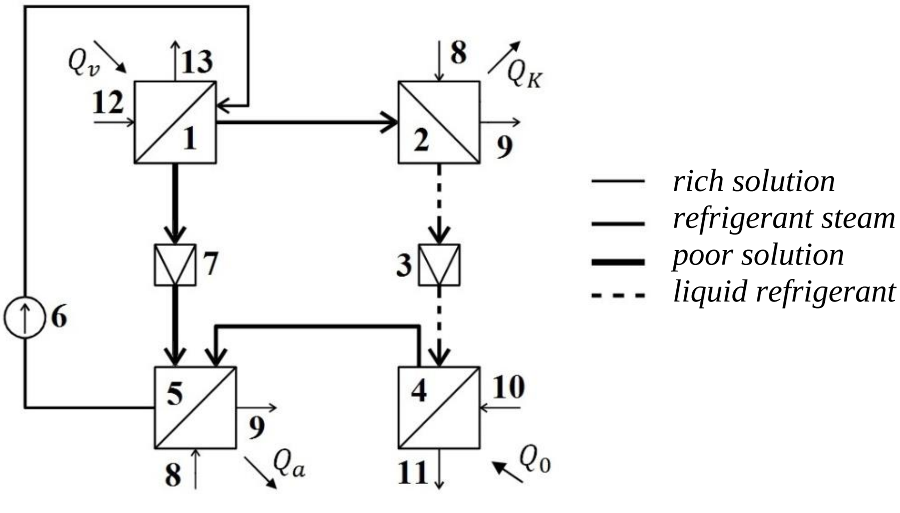


Fig. 5.4. Diagram of the absorption circuit [9]:
1 – vaporizer, 2 – condenser, 3 – throttling valve RV1, 4 – evaporator,
5 – absorber, 6 – pump, 7 – throttling valve RV2, 8 – inflow of cooling medium,
9 – outflow of cooling medium, 10 – inflow of cooled medium, 11 – outflow of cooled medium, 12 – inflow of medium for heating of desorber,
13 – outflow of medium for heating of desorber

The process is similar to that of a vapour circuit, beginning with the evaporation of the refrigerant vapour from the vaporiser. The vapour is liquefied in the condenser and is fed into the evaporator by the throttling valve *RV1*, where it is evaporated at low pressure by the input of heat Q_0 from the cooled medium. The vapour from the evaporator is thickened in the absorber by absorbent which is not completely pure since it contains a small amount of the dissolved refrigerant and is accordingly termed a poor solution; after absorption, a so-called rich solution is made of it. Absorption heat Q_a, appearing after absorption, must be drawn off with cooling water. The rich solution is then transferred by the pump to the heating desorber, boiled, and divided into two phases:

- vapour, containing a large amount of refrigerant but also a certain amount of absorbent (steam),
- poor solution, containing mostly water.

The vapour is fed into the condenser and the poor solution goes back to the absorber through the throttling valve *RV2*.

The cooling circuit described does not work with optimal efficiency because the boiling poor solution from the desorber must be cooled down by the water in the absorber until it is capable of absorbing the vapour, and the cold rich solution must be first heated to boiling point. This deficiency can be overcome by installing a heat exchanger (Fig. 5.5), by which a reduction of the consumption of boiling heat and of water for cooling the absorber is achieved.

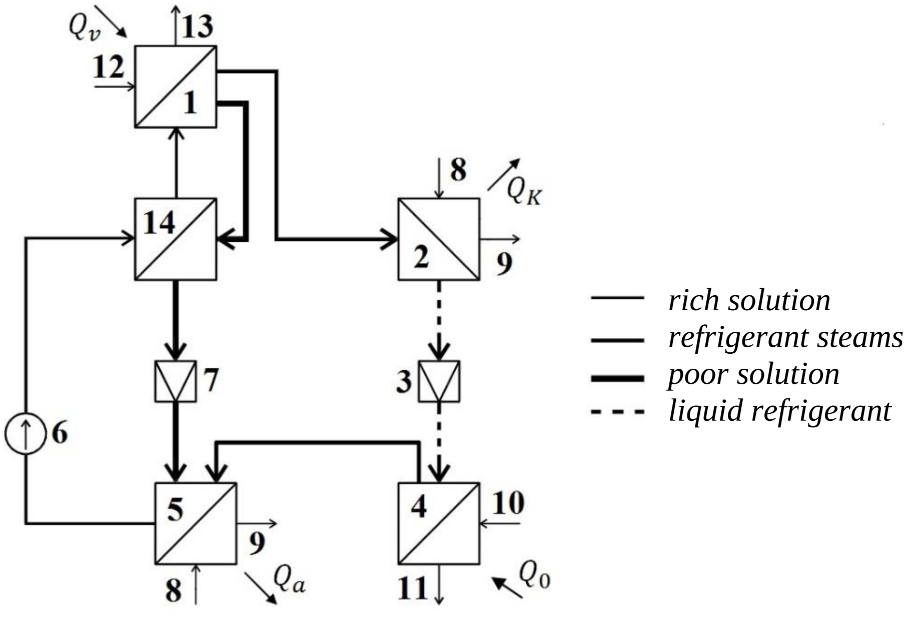


Fig. 5.5. Absorption circuit with improved cooling factor [9]:
1 – desorber, 2 – compensator, 3 – throttling valve TV1, 4 – evaporator,
5 – absorber, 6 – pump, 7 – throttling valve TV2, 8 – input of refrigerant,
9 – output of refrigerant, 10 –input of cooled medium, 11 – output of cooled medium,
12 – input of medium for heating in desorber, 13 – output of medium for heating in desorber,
14 – heat exchanger

COOLING APPARATUSES

In the wider sense, cooling technology works to obtain temperatures from about $20\ °\mathrm{C}$ to theoretically absolute zero, and is divided into two independent fields with their own specifics:

- the field of *cooling technology*, which in the food industry is divided into conservation by *refrigeration* (refrigeration, storage, delivery) and conservation by *freezing* (freezing, storage, delivery). The limit is the freezing point of cellular juices, which occurs in the area of $-0{,}2$ to $-1{,}2\ °\mathrm{C}$,
- the field of *cryogenics*, which works with temperatures around $120\ \mathrm{K}$ ($-153\ °\mathrm{C}$).

If we also include heat pumps in this overview, the total temperature range expands to about $100\ °\mathrm{C}$ (with consideration of economically bearable increases in heating).
According to the requirements for gaining heat according to the individual technologies and methods of removing heat from products, we can divide cooling equipment into:

- *cooling by air,*
- *cooling by a cooling (immersion) fluid,*
- *cooling by a boiling fluid,*
- *cooling by contact.*

With cooling by *air,* the process works by the circulation of cooling air provided by fans. The heat and the moisture from the product go into the air, which takes it to the air cooler (evaporator), where hoarfrost cover is gradually formed. The cooled and dried air returns to the cooling area. The energy necessary for the movement of air is changed by the resistors into heat which, as lost, must also be removed by the cooling equipment. By increasing the speed of the flowing air, the coefficient of the heat exchange from the product to the air increases, but the resistances increase at speed squared. Air speed runs from 4 to $10\ \mathrm{m.s^{-1}}$.
From the standpoint of construction, this type of heat reduction is applied in tunnels, belt equipment and fluid equipment.
The tunnel space is composed of an insulated, most frequently walled, corridor a little larger than the dimensions of a double-hung freezer door. The length of the tunnel runs from 5 to 20 m. For the most part, several tunnels are combined next to each other. On both sides of the tunnel or group of tunnels are cooled handling rooms (pre-tunnels), by which the large temperature difference between the warm operating areas and the tunnels is reduced.

Belt cooling equipment uses conveyor belts (linked, mesh or plastic), on which the product is directly placed on trays, skids and the like. This method is most suitable for smaller products.

Fluid cooling equipment is mostly used for freezing small foodstuffs (berries, small fruit, sliced vegetables, etc.) for which other freezing methods are not suitable due to significant air gaps. Freezing time runs from 3 to 10 minutes, and the fluid layer is high, from 25 to 100 mm.

LIST OF SYMBOLS

Q_a	–	amount of heat removed from absorber	(J)
Q_v	–	amount of heat brought into desorber	(J)
Q_K	–	amount of heat removed in condenser	(J)

Q_0 – amount of heat brought into evaporator (J)
T_{s1} – temperature of cooled medium on entry to condenser (K)
T_{s2} – temperature of cooled medium on exit from condenser (K)
T_{w1} – temperature of cooling medium on entry to condenser (K)
T_{w2} – temperature of cooling medium on exit from condenser (K)
T_0 – evaporation temperature of cooling medium (K)
δ – temperature differences (K)

6 HEAT PUMPS

Under conditions of diminishing world supplies of primary energy resources, efficient usage is becoming a significant feature of energy saving. Fuel and energy conservation can be achieved by means of heat pumps using resources on a low-temperature level. However, the exploitation of such resources can become feasible only after the introduction of devices capable of transforming low-temperature energy to higher levels suitable for practical application. This transformation, the "repumping" of energy to higher temperatures, depends on the supply of other energy of higher quality than electric, mechanical or high-temperature energies. A diagram of the stated transformation is given in figure 6.1.

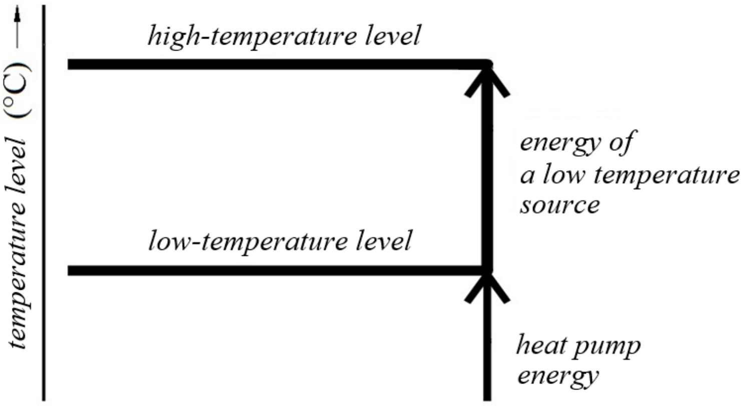


Fig. 6.1. Principle of transformation of energy flows from low temperatures to higher [9]

Non-traditional energy resources used by heat pumps for the most part function up to a temperature level of 30 °C and are from a variety of sources. These include water from rivers, lakes, wells, waste water from swimming pools, partially used geothermal water, heat from external air, waste air from industrial sites and operations, and also heat from the soil and cellar spaces.
Heat pumps are in principle cooling equipment; the difference is only in the understanding of their function – we use coolness from cooling equipment, and heat from heat pumps. The majority of heat pumps are of the compressor type.

Heat pumps are devices that allow heat to be taken from the surrounding environment, transferring it to a higher thermal level and supplying it to facilities – heating units, exchangers, and the like, for the purposes of heating utility water.

The principle is a closed cooling circuit similar to that of refrigerators, in which heat is removed from one side and given to another piece of equipment (with fridges, only air). The refrigerator takes heat from the interior area by means of an evaporator, and accordingly from the food stored in it. The heat is passed through the system to a condenser, from where it escapes freely into the atmosphere. The desired effect is a reduction of the temperature in the cooling area of the fridge and the removal of heat from foods. Heating of the air is just an undesired result of the operation. Heat pumps cool the air, water (natural or utility) or the ground rather than food. The heat taken from such inexhaustible resources by the heat pump is delivered to the heating system or an exchanger for the heating of utility water. The desired effect is an increase of temperature.

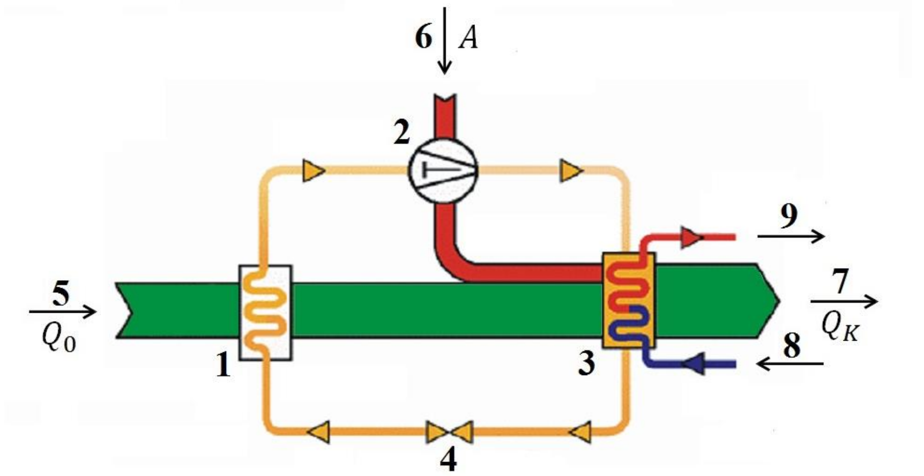


Fig. 6.2. Heat pump diagram [4]:
1 – condenser, 2 – compressor, 3 – condenser, 4 – expansion valve,
5 – heat gained from the surrounding environment (water, air, ground),
6 – supplied electric energy, 7 – total heat gained (heating heat),
8 – recirculated water, 9 – heating water

Figure 6.2 is a diagram of a compressor heat pump. The energy balance of heat pumps is given by the equation:

$$Q_K = Q_0 + A \tag{6.1}$$

where

Q_K	–	condensed utility heat as a product of a heat pump	(J)
Q_0	–	low-temperature source of heat that a given locality provides	(J)
A	–	work delivered to a heat pump	(J)

Heat pumps are made up of four basic parts:

- ***a compressor*** – compresses the refrigerant vapour supplied from the evaporator in the condenser by means of the mechanical energy supplied to the compressor,
- ***a condenser*** – in it takes place the cooling and liquefying of the refrigerant vapour by the exterior heat flow used a source of heat energy,
- ***an expansion valve*** – reduces the pressure of the liquid refrigerant from the condenser to low pressure in the evaporator,
- ***an evaporator*** – in it takes place the evaporation of the refrigerant by means of the heat flow gained from the surrounding environment.

Vaporization of the refrigerant occurs in the evaporator of the heat pump and the liquid is changed into a gas, which is then compressed by the compressor. The compression causes the gas to be heated to a temperature at which the gas in the condenser is vaporized. Therefore, it changes its state and gives off to its surroundings energy that may be further used. In the expansion valve the refrigerant is compressed to the original low pressure, and the circuit is repeated.

Basic types of heat pumps:

- air-water,
- water-water,
- ground-water.

AIR - WATER HEAT PUMP

An arrangement in which external air is used as a heat source. Through the external unit (compressor, fan, evaporator) air is drawn in, and from this is obtained heat energy, and then this heat (cooled) is sent back to the external environment. The internal equipment (condenser, bivalent electric furnace, circuit pump) is situated in the building and produces heating water and also utility water. Modern heat pumps work reliably even at very low outside temperatures – 5 °C to – 18 °C; a small electric heater may be added according to need.

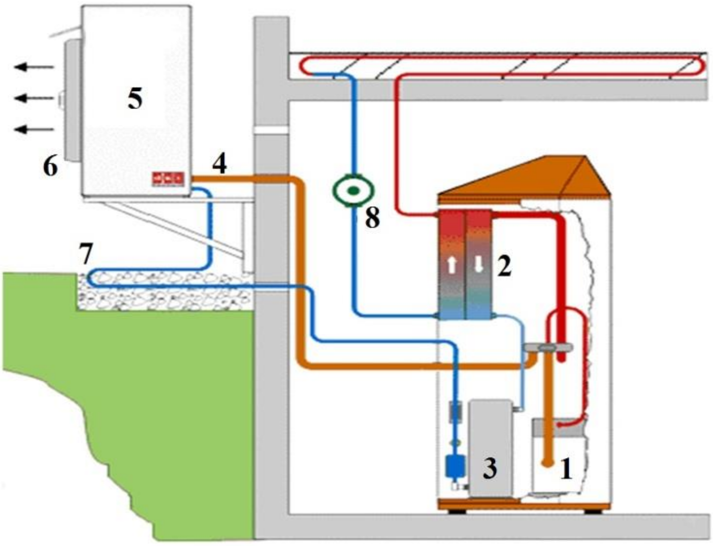


Fig. 6.3. Diagram of air-water heat pump [4]:
1 – compressor, 2 – heat exchanger, 3 – pump, 4 – injector valve,
5 – air evaporator, 6 – fan, 7 – gravel bed under condenser,
8 – circuit pump, 9 – sub-floor heating

WATER - WATER HEAT PUMP

The most common are so-called open systems. As sources of heat, wells or surface water from lakes and rivers with a minimal temperature of 8 °C are considered suitable. So water is taken from a source (usually a well) and run through the heat pump's heat exchanger (evaporator). This takes away some of its heat, and then it is returned to the source.

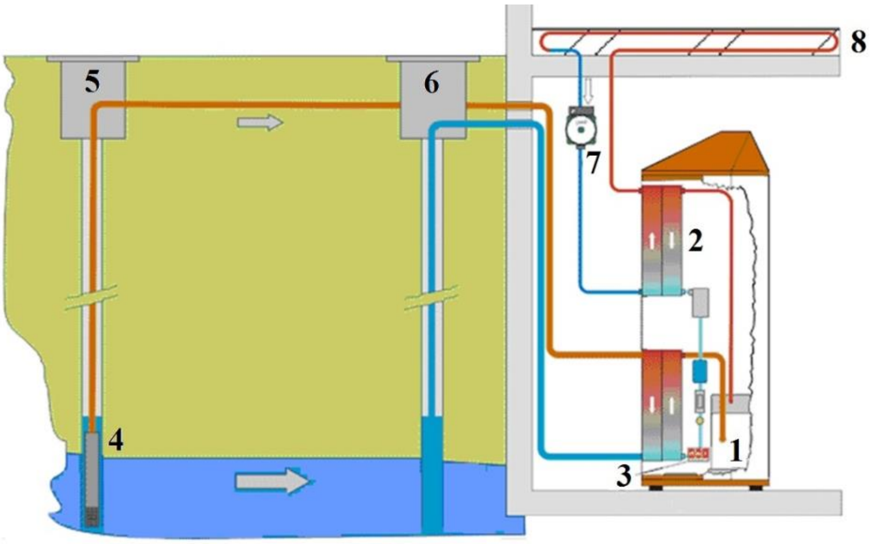


Fig. 6.4. Diagram of a water-water heat pump [4]:
1 – compressor, 2 – heat exchanger, 3 – injector valve,
4 – submersible pump, 5 – source well, 6 – discharge well,
7 – circuit pump, 8 – sub-floor heating

GROUND - WATER HEAT PUMP

If a sufficiently large area of ground is available, this is an ideal heat pump. In a plastic ground collector placed at least 20 cm under the freezing layer of the earth so that the ground becomes a year-round stable heat source, water (antifreeze mixture) is circulated and repeatedly cooled by the heat pump heat exchange and so heat is collected from it. It runs through the ground collector where it is heated up several degrees by the earth’s heat, and the cycle is repeated.

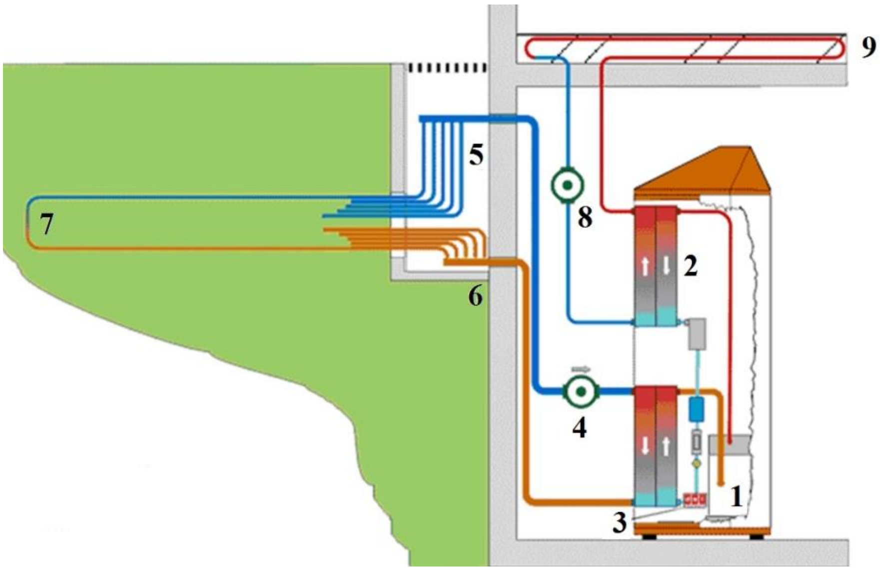


Fig. 6.5. Diagram of a ground-water heat pump [4]:
1 – compressor, 2 – heat exchanger, 3 – injector valve,
4 – brine circuit pump, 5 – brine distributor, 6 – brine collector,
7 – ground collector, 8 – circuit pump, 9 – sub-floor heating

USAGE OF HEAT PUMPS

Heat pumps are complex engineering equipment. To determine whether they can be a practical solution, the following is important:

- consideration of the low-temperature heat source possibilities for a heat pump provided by a given locality,
- thermal input requirements for a given temperature range which the heat pump can cover through its heat output,
- according to the source temperature and the required heat output for a desired temperature, find the effectiveness of the heat pump's operation.

One of the most important parameters for judging the effectiveness of the heat pump's operation is the use of tariff electric energy for heavy users of electric energy, since the kilowatt hour price for the energy needed to drive the compressor is a significant item. Small consumers have higher charges per kWh than large consumers. This fact must be taken into consideration in the calculation of costs for operating a heat pump when negotiating a kWh charge with the electric energy supplier.

The main characteristic for heat pump efficiency is the effective performance number ε, which is defined as the ratio of the profit from the heat pump Q_K to the work supplied A:

$$\varepsilon = \frac{Q_K}{A} \tag{6.2}$$

or

$$\varepsilon = \frac{HEATING\ PERFORMANCE}{ENERGY\ INPUT} \tag{6.3}$$

The performance number is therefore an expression of the ratio between the invested electric energy and the energy gained in the form of heat in the form of heating. The performance number is different for different styles and types of pumps [45].

- With air-water heat pumps, the performance number is significantly reduced over the course of the year. In summer, the air has an optimal temperature so the performance number is at its highest. As the air temperature drops, the performance number will also be reduced because the evaporator is being heated by a medium with an ever decreasing temperature. The critical value for air temperature is -20 °C, when the air-water heat pump stops working at full efficiency and approaches performance number 2. In light of the fact that the heat pump works most of the year in favourable temperature conditions, the performance number fluctuates around a year-round value of 3,5.
- The water-water heat pump would seem to be a stable variant with a high performance number as long as the source of quite warm water is constant, and its temperature does not fall significantly even in winter. In summer, the performance number of the water-water heat pump can rise to 6, while it can fall to 4 in winter.
- The ground-water heat pump can achieve performance number 5, but only in cases where wells are optimally dimensioned and where the anti-freeze fluid can be sufficiently heated during its circulation. During winter, the sub-soil temperature decreases steadily, which is shown by the dropping of the performance number, which might drop down to a value of 3,5.

Heating (condensation) performance $\dot{Q}_K$ (W) and electrical input P (W) (i.e. work A per time unit) are stated by the manufacturer at determined temperatures of heat pump operation, at condensation temperature t_C and evaporation temperature t_0. Thanks to these data, the performance number ε can be calculated from the equation:

$$\varepsilon = \frac{t_C}{t_C - t_0}\,\eta_{HP} \qquad (6.4)$$

where

η_{HP} – comparative efficiency of the heat pump (1)

An important issue in deciding to install heat pumps is the saving of fuel and also the question of what the minimal value of the performance number $\varepsilon_{\mathrm{MIN}}$ should be to secure a society-wide saving of fuel. If we consider the efficient production of electric energy, including distribution losses η_{DL} and a classical boiler working with efficiency η_B, the minimal performance number value must be:

$$\varepsilon_{\mathrm{MIN}} = \frac{\eta_B}{\eta_{DL}} \qquad (6.5)$$

For replacing conventional heating with heat pumps with values η_D a η_B the non-equation below is used:

$$\varepsilon \geq \varepsilon_{\mathrm{MIN}} \qquad (6.6)$$

If this condition is fulfilled, we achieve society-wide primary energy savings by installing heat pumps.

LIST OF SYMBOLS

t_C – condensation temperature (K)
t_0 – evaporation temperature (K)
P – input (W)
Q_K – condensed utility heat as product of heat pump (J)
Q_0 – low-temperature source of heat provided by given location (J)
$\dot{Q}_K$ – heating power (W)
A – work supplied by heat pump (J)
ε – coefficient of performance (1)
$\varepsilon_{\mathrm{MIN}}$ – minimal performance number (1)
η_{DL} – efficiency of distribution losses (1)
η_B – efficiency of boiler (1)
η_{HP} – comparable efficiency of heat pump (1)

7 MASS TRANSFER

PHASE EQUILIBRIUM OF TWO-COMPONENT SYSTEMS

In general, a closed system is in equilibrium if its state is such that spontaneous changes cannot take place in it. This means that forces or potentials which could bring about such changes are in equilibrium.
If two phases are present (fluid – vapour), they act as a closed system in which their mutual equilibrium is achieved. Each phase, however, forms an open system in which changes in composition and volume may occur. To secure overall equilibrium, it is necessary to achieve equilibrium in each of the phases in the system.

In systems under the influence of driving forces, spontaneous actions take place at a determined speed - for example, with a spontaneous flow of fluid from a place with higher pressure to a place where the pressure is lower. In the spontaneous flow of heat in non-insulated systems moving from a system with a high temperature to a system with a lower temperature, the flow of the mass amount of a given composition moves from the position with higher chemical potential to the position with lower chemical potential. The speed of these events lessens over the course of time (because the driving forces are reduced) and after reaching a balanced state it equals zero (otherwise stated as at equilibrium, driving forces equal zero, or the difference in potentials is zero). In general, a spontaneous event occurs until a state of equilibrium is achieved. A system is in equilibrium when spontaneous changes (i.e. changes not caused by external impact) can no longer occur in the system. The conditions under which a system is in equilibrium are reproducible and can be described by a set of properties which are a function of the state, so-called properties (state quantities) which are not dependent on what happened to the state prior to its achieving equilibrium.

A system of absolute equilibrium cannot exist. Equilibrium can only be partial with respect to what physical event occurs in the confined area of the space.
From the standpoint of the thermodynamic process, the following partial equilibriums may be mentioned:

- ***internal equilibrium***

This is in a homogeneous system, for example a homogeneous solution with equal concentration throughout the entire volume and with equal temperature and pressure at each point. The criterion of internal equilibrium is that a change of each intensive state function dependent on position equals zero, i.e. the state quantity at each point of the system is equal ($\mathrm{d}p/\mathrm{d}z = 0$, $\mathrm{d}T/\mathrm{d}z = 0$, $\mathrm{d}C_i/\mathrm{d}z = 0$, etc.).

- ***mechanical equilibrium***

For example, with compression and expansion of a gas, the pressure of the gas in a cylinder p is equal to the pressure on the piston from the environment p_{ok}. In this case, the equilibrium criterion is $p = p_{ok}$.

- ***heat equilibrium***

Two fluids with equal temperature T are in the tubes and in the space between the tubes of the heat exchanger T_{ok}. In this case, the equilibrium criterion is $T = T_{ok}$.

- ***phase equilibrium***

Fluid-vapour equilibrium in a binary system, e.g. benzene – A, toluene – B. In this case, the equilibrium criterion is the equality of the chemical potentials of the compositions in both phases, i.e.

$$\mu_A^{(g)} = \mu_A^{(l)} \tag{7.1}$$

- ***chemical equilibrium***

For a reaction of the type A ↔ R (note: material A by reaction changes into material R) in equilibrium, the balanced constant is equal to the ratio of the concentration of material R to the concentration of material A, i.e.

$$K_c = \frac{c_{R,e}}{c_{A,e}} \tag{7.2}$$

The criterion of chemical equilibrium in the given case is therefore

$$c_{A,e} = \frac{c_{R,e}}{K_c} \tag{7.3}$$

According to the Gibbs phase rule, the system of two components may be in from one to four phases. From the standpoint of separation processes, the most frequent are two-phase, possibly three-phase, systems. The phases create compounds which, from the viewpoint of thermodynamic behaviour, can be divided into ideal and real.

The formation of solutions is conditioned by the size of intermolecular forces. In ideal solutions, the attraction forces are equal between the molecules of different and similar kinds. In the case that these forces are different, they form a real compound. The external manifestation of a real solution is that a heat effect occurs (e.g. heat is released in the mixing of sulphuric acid with water) as well as volume contraction (e.g. in the mixing of two pure fluids, the volume of the solution is somewhat less than the total of the volumes of the pure constituents).

From the standpoint of dissolvability, compounds can be:

- mutually completely dissolvable,
- partially dissolvable,
- completely insoluble.

Ideal compounds mainly include mixtures of vapours and gases (with extremely high pressures however they form real compounds) and fluid compounds in which the materials have a similar structure and molecule size (these include for example compounds of homologues, such as benzene – toluene, methanol – ethanol and similar).

The following text will deal with the description of a balanced binary system in which the phases are ideal compounds. The constituents in the fluid phase are mutually completely dissolvable i.e. they form a so-called true solution.

PRINCIPLE OF THE PROCESS

When two fluids dissolve, the following cases may occur:

- the fluids are completely dissolved and form one fluid phase which, under certain conditions, may be in equilibrium with the vapours of the fluid (e.g. water and alcohol),

- if the fluids when mixed are only partially dissolved or completely undissolved (e.g. water and toluene), then two fluid phases and one vapour phase made up of the vapours of the fluids exist separate from each other.

The principle of the process for separating solutions depends on the differing boiling temperatures of the fluids, whether completely dissolved or undissolved. If such a system is heated to a certain temperature, the constituent that is more volatile begins to vaporise more intensively than the other one. Therefore, the vapours will be enriched by the constituent with a lower boiling point. If the vapour phase is then cooled, the constituent that has the lower temperature will be the first to condense and so fluid phase will result, significantly enriched by the more volatile constituent.

Examples of separating multi-component solutions:

- *fluid solution*,
  - mixture of fluid and gas constituents (dissolved CO_2 gas in fluid H_2O),
  - mixture of fluid constituents (ethyl alcohol solution C_2H_5OH and water H_2O),
  - fluid and solid constituents (sugar in water solution),
- *gas solution – mixtures of gases and vapours*,
  - vapour mixture (mixture of ethyl alcohol and water vapours),
  - gases mixture (mixture of CO_2 and air),
  - mixture of gases and vapours (mixture of vapours of hydrocarbons and air),
- *solid solution*,
  - mixture of solid constituents.

OCCURRENCE

One example of equilibrium in a two-compound system is the oxidization of iron. This is a process in which oxygen in a gaseous form reacts with iron in the formation of iron oxide (Fe_2O_3). This is a spontaneous and slow process that occurs whenever oxygen has contact with unoxidized iron or when in a closed system there is enough oxygen for the process to continue. If this process stops, for example as a result of the covering of the surface of the iron with iron oxide, there occurs phase equilibrium between oxygen in a gas state and iron oxide in a solid state.

Another example is champagne. From the fluid phase, saturated carbon dioxide CO_2 moves progressively into the space above the fluid surface until equilibrium occurs between the partial pressure of the CO_2 above that level and its volume dissolved in the fluid. This is described in the Henry constant, in dependence on temperature.

Accordingly, if champagne at room temperature is opened, the solubility of the CO_2 in the liquid is less, the partial pressure of the CO_2 above the surface is greater, and it usually ends with the cork popping out. But if the champagne is cooled, the Henry constant value is lessened, the partial pressure of the CO_2 above the surface is lessened as a result of the fact that a greater amount of CO_2 is dissolved in the liquid phase (in the wine), and the cork is less likely to fly out of the bottle.

In industry, this knowledge is applied to the distillation of alcoholic beverages, oil refining, and similar processes.

Driving forces
The driving forces of the process are:

- change of the heat of the solution,
- change of the pressure of the solution,
- different volatility of the components,
- difference in chemical potential.

COMPARISON OF SINGLE-COMPONENT AND TWO-COMPONENT SYSTEMS AT BOILING TEMPERATURE

At the beginning of the description of the equilibrium, it will be useful to compare the behaviour of a single-component fluid - vapour system with a two-component system with unrestricted soluble fluids as illustrated in the diagrams $(p - T)$ and $(p - v)$.

PHASE EQUILIBRIUM OF A SINGLE-COMPONENT SYSTEM

In figure 7.1 is illustrated the course of evaporation of a pure fluid under constant pressure $[p]$ and temperature $[T]$.

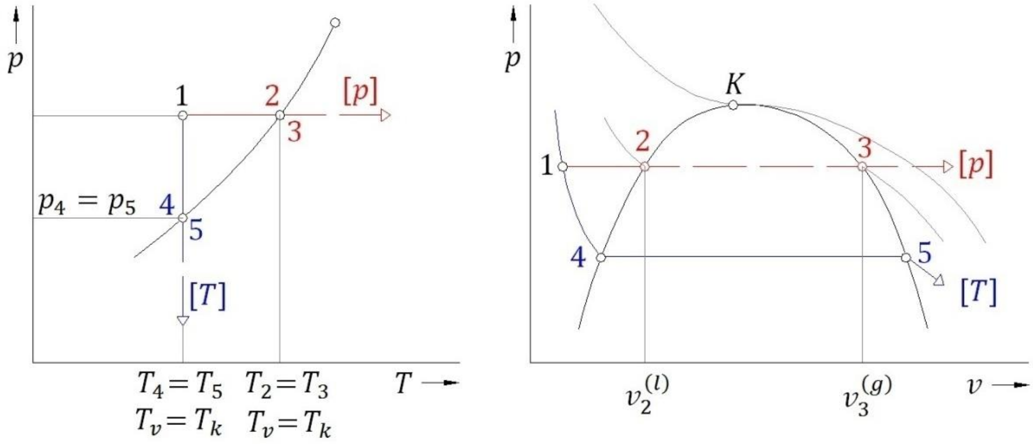


Fig. 7.1. Behaviour of a single-component system during evaporation [6]

- ***Behaviour of a single-component mixture at constant pressure*** $[p]$ ***- isobaric heating***
  - The initial state is illustrated by point 1.
  - The change in the state of the fluid from point 1 to point 2 is brought about by isobaric heating, during which the temperature of the system increases to the boiling point (with the given pressure).
  - State 2 at $[p, T_2]$ is the point at which the fluid starts to boil.
  - Between points 2 and 3 the fluid starts to boil and isobaric - isothermal evaporation occurs.
  - At point 3 the fluid is right at the state of steam vapour, i.e. point 3 is the point of condensation of vapour – dew point.
  - After point 3 isobaric heating of the vapour occurs.

- ***Behaviour of a single-component mixture at constant temperature*** $[T]$ – isothermal ***change of pressure***
  - The initial state is illustrated by point 1.

- The change in the state of the fluid from point 1 to point 4 is brought about by isothermal reduction of the pressure.
- Point 4 represents the boiling point at which the fluid starts to boil.
- Between points 4 and 5 isobaric – isothermal evaporation takes place. At point 4 the first bubble of the vapour phase appears. At a constant temperature corresponding to the isotherm $[T]$ of the preceding points 4 – 5, boiling takes place between these boiling points. In point 5 the whole compound is in the state of vapour.
- In point 5 the whole fluid is in state of vapour.
- Below point 5 isothermal heating of the vapour takes place.
- T_k is the isotherm of the critical temperature.

PHASE EQUILIBRIUM OF A TWO-COMPONENT SYSTEM

Graphs of a vaporising two-component soluble mixture are shown in figure 7.2 and are different from a single- component mixture.

When a two-component mixture is formed of two materials:

- material A (more volatile than material B)
- material B (less volatile than material A)
- their mutual ratio is such that, for example, material B is in a molar X_B system

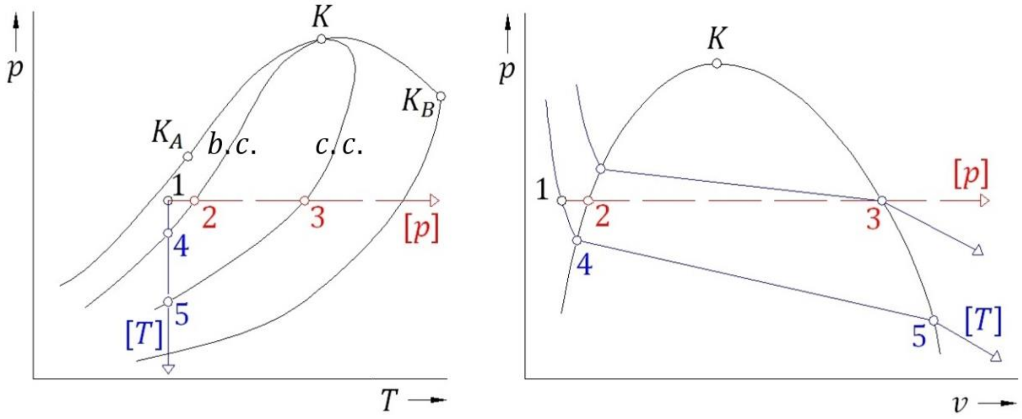


Fig. 7.2. Behaviour of a two-component system during vaporisation [6]:
$b.c.$ – boiling curve, $c.c.$ – condensation curve

- ***Behaviour of a two-component mixture under constant pressure $[p]$ – isobaric heating***
  - The starting state is shown by point 1.
  - When the liquid at a constant pressure reaches the temperature given by point 2 (point of boiling of the two-component liquid system) the liquid begins to boil and the vapours are made richer than the liquid by the more volatile component A.
  - The liquid begins to be degraded by the more volatile component. If the boiling is to continue, the temperature of the system must be increased.
  - The temperature therefore must increase to point 3, where the entire liquid will be in a steam vapour state.
  - After point 3, isobaric heating occurs again.

- ***Behaviour of a two-component mixture at constant temperature* $[T]$ *– isobaric pressure change***
  - Isobaric evaporation takes place between points 4 and 5.
  - If the pressure in the system is isothermally reduced from point 1 to point 4, the liquid begins to boil.
  - Due to the gradual degradation of the liquid by the more volatile component A, the boiling can only be maintained if the pressure in the system is continually reduced to point 5.
  - At point 5, the final part of the liquid will be evaporated.
  - Below point 5, heating of the vapour again takes place.

From the preceding text it follows that the boiling point during the whole time of evaporation changes in dependence not just on the pressure but also on the makeup of the liquid. Point 2 and point 4 are referred to as the boiling points. The boiling curve is found by combining all the points of the beginning of boiling. Point 3 and point 5 are referred to as the dew points. The condensation curve is found by joining all the dew points of the beginning of condensation.

Both of these curves form a loop which closes the two-phase area of liquid-vapour for a system of the given composition. A different loop is found for each composition. All components have a common envelope line that lies between the critical points of the given liquids K_A, K_B. The point of contact of each loop with the common envelope line is the critical point of the given mixture.

LIQUID-VAPOUR EQUILIBRIUM

This type of equilibrium appears in the separating of liquid solutions by distillation (rectification) and vapour solutions by partial condensation. Rault dealt with the equilibrium of binary mixtures. He found that with equilibrium of liquid-vapour at a given temperature, the partial pressure of a component above the ideal solution equals the sum of the equilibrium pressure of the saturated vapours of the pure component and the molar fraction of the component in the liquid phase.

$$p_i = p_i^0 \, x_i \tag{7.4}$$

The partial pressure of a component in vapours according to Dalton's law is a sum of the total pressure and the molar fraction of the given component

$$p_i = p \, y_i \tag{7.5}$$

And the sum of the partial pressures equals the total pressure

$$\sum_i p_i = p \tag{7.6}$$

By combining (7.4) and (7.5) we get a relation which, after modification, describes the equilibrium by means of the molar fractions

$$y_i = \frac{p_i^0\, x_i}{p} = K_i^0\, x_i \tag{7.7}$$

The ratio of the molar fraction of the component in the light phase to the molar fraction of the component in the heavier phase is called the equilibrium ratio K_i^0 (equilibrium-separating coefficient).

$$K_i^0 = \frac{y_i}{x_i} = \frac{p_i^0}{p} \tag{7.8}$$

The separation of liquid solutions by distillation is in practice performed under constant pressure, and therefore in the following text we will look at the isobaric equilibrium of liquid-vapour. The component that has a lower boiling temperature is the so-called more volatile component (component A), while the second component has a higher boiling temperature (less volatile, component B).
The partial pressures of components A and B can be expressed by Rault's law

$$p_A = p_A^0\,(T)\, x_A \tag{7.9}$$

While for a two-component mixture is valid

$$x_A + x_B = 1 \tag{7.10}$$

so

$$p_B = p_B^0\,(T)\,(1 - x_A) \tag{7.11}$$

The sum of the partial pressures is the total pressure of the system

$$p = p_A^0\,(T)\, x_A + p_B^0\,(T)\,(1 - x_A) \tag{7.12}$$

By modification of the equation (7.12) (by expressing the molar fraction in the liquid as a function of the equilibrium pressures of the pure components) we get a relation that states the dependency on temperature of the boiling temperature of the liquid in equilibrium (boiling temperature as a function of the composition in the liquid is in an implicit form)

$$x_A = \frac{p - p_B^0\,(T)}{p_A^0\,(T) - p_B^0\,(T)} \tag{7.13}$$

In the equilibrium diagram $T = (x_A,\, y_A)$ this equation describes the boiling curve c_{boil} (Fig. 7.3). The condensation curve c_{con} is described by the equation

$$y_A(T) = \frac{p_A^0\,(T)}{p} x_A = \frac{p_A^0\,(T)\,[p - p_B^0\,(T)]}{p\,[p_A^0\,(T) - p_B^0\,(T)]} \tag{7.14}$$

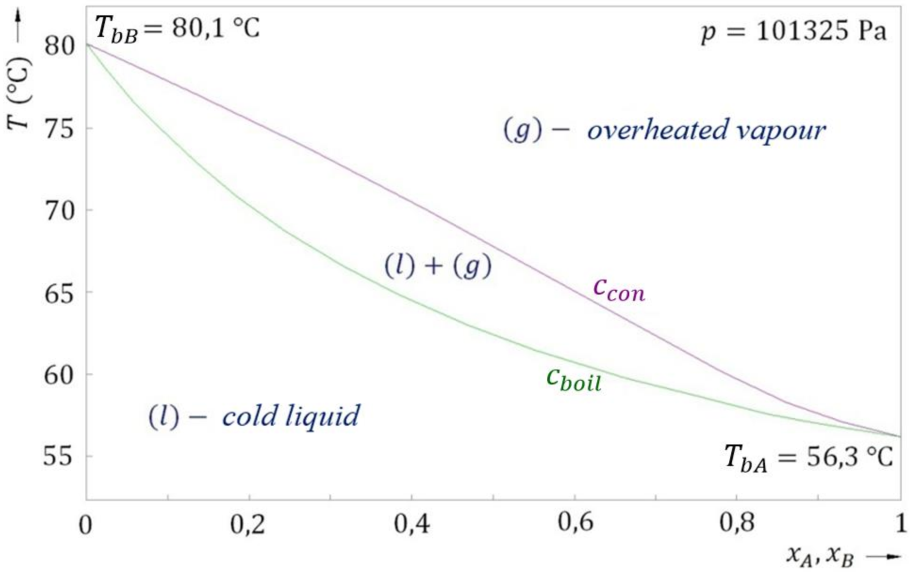


Fig. 7.3. Equilibrium liquid-vapour diagram for acetone-benzene system [6]

The equilibrium diagram of a two-component system is presented in figure 7.3. The boiling curve and the condensation curve in the diagram illustrate three areas: area (l) the area of the cold liquid, area (g) the area of the overheated vapour and between the boiling curve c_{boil} and the condensation curve c_{con} the area in which the two phases i.e. the liquid phase (l) and the vapour phase (g) (saturated vapour) exist next to each other in equilibrium.
The equilibrated ratios of the components A and B gives the so-called relative volatility α_{AB}.

$$\alpha_{AB} = \frac{K_A^0}{K_B^0} = \frac{p_A^0\,(T)}{p_B^0\,(T)} \tag{7.15}$$

The relative volatility of an ideal system is dependent only on temperature. Two materials from a solution can be best separated from each other through distillation as a function of the difference in their boiling temperatures, i.e. the greater is their relative volatility.
The equilibrium diagram of a liquid-vapour two-component system is often expressed in the form

$$y_A = \frac{\alpha_{AB}\, x_A}{1 + (\alpha_{AB} - 1)x_A} \tag{7.16}$$

In the equilibrium diagram (Fig. 7.4) depiction of this function is the so-called equilibrium line $y_A = f_{eq}(x_A)$.

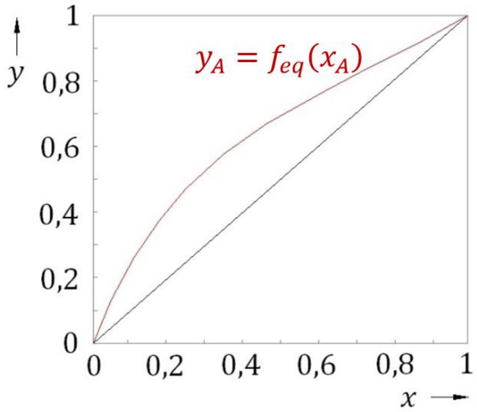


Fig. 7.4. Equilibrium liquid-vapour diagram for acetone-benzene system on x - y coordinates [6]

In figure 7.5 is shown an example of the isobaric evaporation of a two-component system A and B with the mole fraction of the more volatile component $x_A = 0{,}4$. On the right part of the figure, the states of systems 1 to 5 are diagrammatically illustrated by cylinders with a stable piston pressure p and with temperatures T_1 to T_5. The initial state of the liquid solution is given by point 1 (T_1, x_{A1}). In heating to temperature T_2 (to state 2 (T_2, x_{A1}) the volume of the liquid is increased due to thermal expansion, and at the same time the first molecules of the vapour phase (state 2" (T_2, y_{A2}) start to be released because the boiling point has been reached. At temperature T_3 (state 3') in the system, two phases exist next to each other in equilibrium: liquid (in state 3' with concentration x_{A3}) and vapour (in state 3" with concentration y_{A3}). The system as a whole, however, still has the concentration $x_A = 0{,}4$. The amount of the individual phases can be determined by the leverage rule, i.e. the amount of substance in both phases is in the ratio of the segments $\overline{3"3}$ to $\overline{3'3}$. After reaching temperature T_4 the last traces of the liquid phase disappear, the system creates only saturated vapour with the concentration $y_{A4} = 0{,}4$. Temperature T_4 indicates the dew point. In heating above temperature T_4 the system arrives at the area of overheated vapour with concentration $y_{A4} = 0{,}4$ and temperature, for example, of $T_{5,}$. The solution boiling temperature during the evaporation changes from temperature T_2 to over T_4, i.e. from the beginning of boiling to the condensation temperature. This state is caused by the increasing concentration of the less volatile component B in the liquid (this means that if we want to keep the liquid boiling it is necessary to constantly increase the system temperature, whereas for a single-component system, as has been mentioned above, the boiling temperature is identical to the condensation temperature). The concentration of the more volatile component in the liquid phase is reduced (the liquid is degraded by the volatile component), while the concentration of the more volatile component in the vapour phase is enriched (the greatest enrichment is at the beginning of boiling).

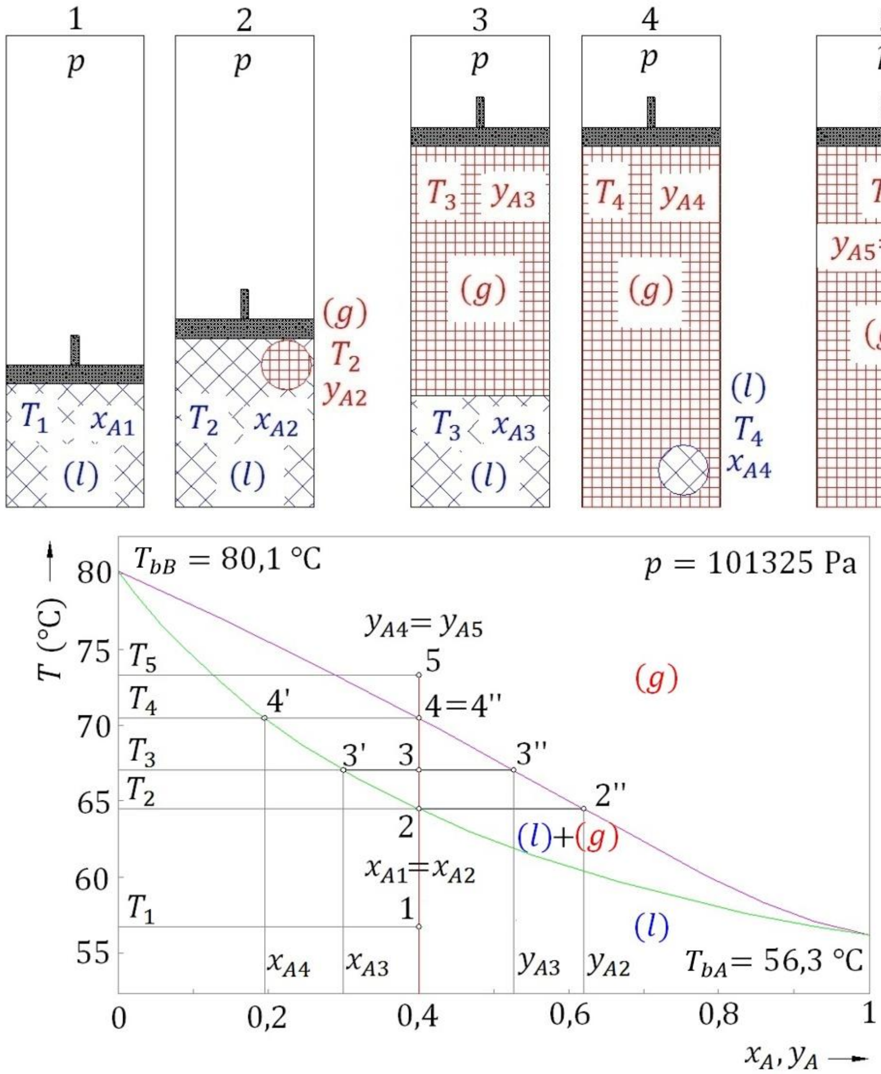


Fig. 7.5 Isobaric condensation of two-component systems [6]

LIQUID-GAS EQUILIBRIUM

The equilibrium of a liquid-gas compound occurs on the separation of the gases by absorption. A system with absorption is composed of an absorbed component, an inert carrier gas, and a solvent. The separation of the components of a gas mixture by absorption is conditioned by their different solubility in the liquid solvent – absorbent.

The solubility of the gas in liquids depends on:

- the partial pressure of the absorbent component,
- the temperature system,
- the chemical nature of the solvent and the dissolved material.

Henry investigated the solubility of gases in liquids. On the basis of measurement, he found that a system in which the components do not mutually react chemically at a given temperature of partial pressure of the absorbed component *i* above the solution is proportional to its mole fraction in the liquid. This constant of proportionality is called Henry’s constant. Its mathematical expression is in the form

$$p_i = H_i\, x_i \tag{7.17}$$

where

H_i – Henry's constant for the given material (stated in the tables) (Pa)

The partial pressure of the component and in the gas is, according to Dalton's law, the sum of the total pressure and the mole fraction of the given component according to the relation (7.5). By combining the equations (7.5) and (7.17) is found the relation which, after modification, describes the equilibrium by the mole fractions

$$y_i = \left(\frac{H_i}{p}\right) x_i \tag{7.18}$$

If the absolute mole fractions are expressed by the relative mole fractions, the relation is found in the form

$$Y_i = \frac{\left(\frac{H_i}{p}\right)\, X_i}{1 + \left(1 - \left(\frac{H_i}{p}\right)\right) X_i} \tag{7.19}$$

The Henry`s constant values, and also the extent of the concentrations in which the quantity H_i is constant, are found experimentally. For solutions, the ideal (at a certain pressure and temperature) H_i values are constant. Henry's constant is therefore best applicable where the solution is more diluted – i.e. where as little gas as possible is dissolved in the liquid.

The graphic representation of the function (7.18) or (7.19) is called the equilibrium straight line or the equilibrium curve. In figure 7.6 is shown the equilibrium line for the NH_3 - H_2O set at pressure $p = 101{,}325$ kPa and temperature 20 °C. Henry's constant at this temperature is $H_{NH3} = 2{,}77.10^5$ Pa.

The solubility of a gas in a liquid is most frequently an exothermic event when the dissolution heat (differential dissolution enthalpy) is $\Delta_{sol}h_{T,i} < 0$. In such a case, Henry's constant increases with the rising temperature, and the solubility of the gas in the liquid decreases. The dependency of Henry's constant on temperature can be described by the relation

$$\left(\frac{\partial \ln H_i}{\partial T}\right)_p = \frac{\Delta_{sol}h_{T,i}}{RT^2} \tag{7.20}$$

And after integration for the constant $\Delta_{sol}h_{T,i}$

$$\ln H_i = A - \frac{B}{T} \tag{7.20}$$

where A is the integration constant and

$$B = \frac{\Delta_{sol}h_{T,i}}{R} \tag{7.21}$$

The values of the A and B constants can be determined by experimental data.

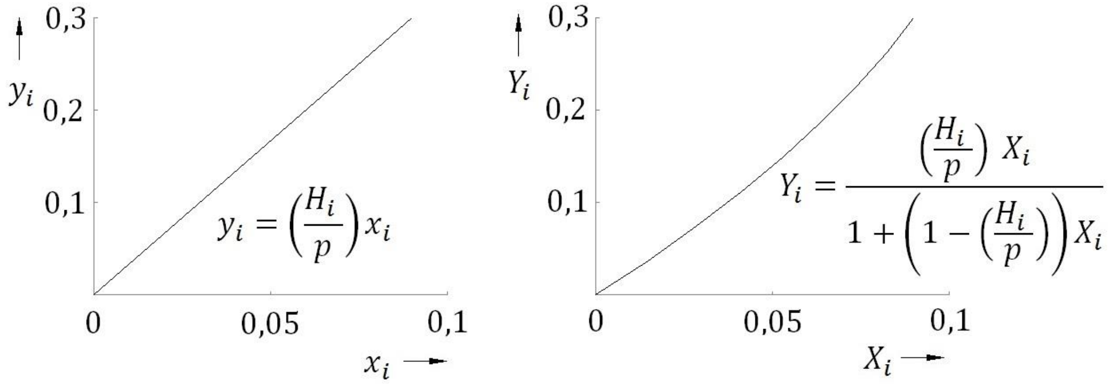


Fig. 7.6. Equilibrium lines for a liquid-gas equilibrium [6]
(dissolvability of NH_3 *in* H_2O *at temperature* $20\ °C$ *and pressure* $101{,}325\ kPa$*)*

The fact that at a given pressure and temperature the composition of the liquid and gas phases is different may be practically used in the separation of the components from liquid solutions. It is used, for example, in the processes known as distillation and rectification.

DIFFUSION PROCESSES

These often occur in the chemical and food industries processes when the compositions of mixtures of materials are changed, but do not go through chemical reactions. Such processes are characterized by the transfer of material, and are called diffusion processes or also separating processes, with one material diffusing into another.

A common trait of diffusion processes is the transfer of a material through a phase interface and its transport in phases towards the phase interface.

A material is most frequently changed between two phases that are in direct contact. The transfer of a material can however occur between phases that are separated by a membrane (cells in living organisms, osmosis, dialysis).

Membrane processes make up a significant group of diffusion processes. The material transfer occurs through a membrane where the mixable phases separate from each other.

In gas mixtures the concentrations are often stated by means of partial pressures. For an ideal gas the state equation applies:

$$p_i\, V = n_i\, R\, T \tag{7.22}$$

where
p_i – partial pressure of component i (Pa)
V – volume ($\mathrm{m^3}$)
n_i – mole amount of component i (mol)
R – universal gas constant ($\mathrm{J.mol^{-1}.K^{-1}}$)
T – temperature (K)

Mole concentration of component i in a mixture is defined as the ratio of the mole amount of component i to the total volume of the mixture:

$$c_i = \frac{n_i}{V} = \frac{p_i}{R\,T} \tag{7.23}$$

Generally, the mole ratio of component i in the gas phase can consequently be expressed:

$$y_i = \frac{c_i}{c} = \frac{p_i}{p} \tag{7.24}$$

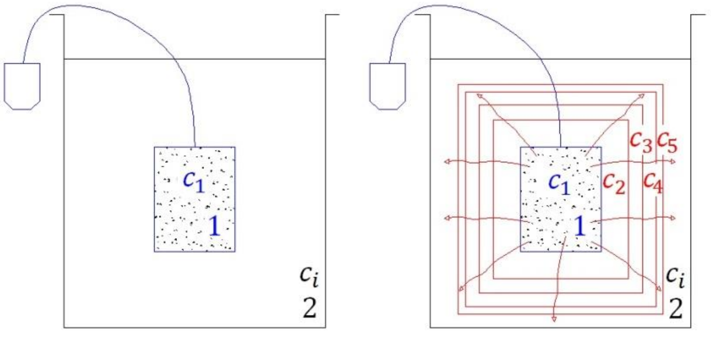
Where the total pressure p is according to Dalton's Law the sum of the partial pressures of the components:

$$p = \sum_{i=1}^{N} p_i \tag{7.25}$$

In a mixture of ideal gases, the mole ratio y_i equals the volume ratio because each kmol of gas under normal circumstances occupies a volume of 22,4 m^3.
The density of component A in a mixture (absolute density concentration of component A) is the ratio of the density of component A in the mixture to the total volume of the mixture:

$$\rho_i = \frac{m_i}{V} \tag{7.26}$$

A typical case of a commonly encountered diffusion process is that of coffee or tea preparation.



a *b*

Fig. 7.7. Diffusion process in brewing tea [6]:
a – concentration of tea at the moment of immersing bag into water,
b – distribution of concentration field in water after given time,
1 – teabag, 2 –water

A teabag (1) is immersed in boiling water (2). The concentration of the tea (this means aromatic materials and colouring) in the teabag is c_1, while at this moment the concentration of the tea in the cup is $c_i = 0$. Diffusion occurs immediately after the immersion in the water. The aromatic materials and colouring progressively expand in a molecular way through the entire contents of the vessel. The greatest concentration is still in the bag and progressively lessens in a direction towards the walls of the vessel. This is a non-stationary process, which means that while it is valid that $c_1 > c_2 > c_3 > c_4 > c_5 > c_i$, with $c_i = 0$, the value of the concentration of the tea in the bag is progressively falling and the other concentrations are rising, including concentration c_i, which after a certain time is also greater than zero. Then there comes a time when all the concentrations are equalled out, so $c_1 = c_2 = c_3 = c_4 = c_5 = c_i = c$. The diagrams in figure 7.7 designate imaginary areas with the same concentrations. It should be noted here that these are truly fictive areas, because the diffusion process is continuous and, with respect to diffusion from one phase to the other, both being homogeneous, there exist no leap changes.

Diffusion is also the basis of every living thing found on the planet Earth. All the cells in living organisms contain membranes, and the processes in them are connected to the transfer of material.

Another typical example of diffusion is the evaporation of liquids to inert gases. This is exemplified by water in a lake that is in contact with air. The water molecules gradually evaporate and penetrate into the air that is above the surface.

Diffusion processes also occur very often in technical praxis since each chemical process also includes the cleaning of raw materials, the separating of mixtures and so on, which make use of the principles of material transfer between phases. Diffusion processes are specific to chemical engineering. They are of fundamental importance:

- in the separation of the basic materials of homogenous and heterogeneous systems; material systems are then the products of material transfers achievable by chemical or biochemical reactions in apparatuses,
- in the cleaning of homogenous and heterogeneous systems; for example flue gas desulphurization or water purification,
- Diffusion processes also include distillation, rectification, absorption, exsorption, extraction, adsorption, and the like; these processes will be mentioned in further sections.

The physical character of resistance and its intensity depend on the hydrodynamic state of the phase. Examples of this are the following basic mechanisms of mass transfer:

- ***molecular mechanisms*** (molecular diffusion or conductivity diffusion),
- ***mechanisms of mass transfer by flowing*** (convection diffusion),
- ***convection mass transfer in the vicinity of phase interface - film theory***.

MOLECULAR MECHANISMS

Conductivity (molecular) diffusion takes place in solid materials, stationary liquids and gases, and similar. It is the transport of material conditioned by a concentration gradient, as a consequence of the moving state of the molecules.

The speed of molecular diffusion with a concentration gradient therefore depends on the molecular state of the phase, i.e. on the properties of the transported component and the environment in which its relocation takes place, as well as on temperature and pressure.

Molecular diffusion can also occur in the gas phase, a phenomenon that has been quite well researched and can be described on the basis of the kinetic theory of gases. Molecular diffusion in liquids has not been so closely studied.

One molecule of the material is a straight-moving particle that collides with other particles in its path, causing a change in its speed and direction. This complex movement of the molecule is therefore reflected in the speed of the transport of the material, which has a small value, and is dependent on pressure and temperature. The quantitative side of molecular diffusion is quite well described by the Maxwell–Stefan theory, according to which the reduction of the partial pressure of the diffusing material in the direction of diffusion for the area of the unit length in the stationary phase is proportional to the relative speed of the movement of the molecule in the direction of diffusion and the sum of the mole concentrations of the materials diffusing against each other:

$$-\frac{\partial p_A}{\partial z} = \beta\, c_A\, c_B\, (u_A - u_B) \tag{7.27}$$

where

$-\partial p_A$	–	reduction of partial pressure of component A, diffusing in the direction of axis z	(Pa)
∂z	–	distance which corresponds to the drop in partial pressure $(-\partial p_A)$	(m)
β	–	proportion coefficient	(1)
c_A	–	mole-volume concentration of component A	$(\mathrm{mol.\,m^{-3}})$
c_B	–	mole-volume concentration of component B	$(\mathrm{mol.\,m^{-3}})$
u_A	–	average speed of movement of component A molecules	$(\mathrm{m.\,s^{-1}})$
u_B	–	average speed of movement of component B molecules	$(\mathrm{m.\,s^{-1}})$

Other arrangements of this equation are dependent on whether the exchange of material between the phases is one-directional or two-directional.

- ***one-directional diffusion***

One-directional diffusion is characteristic for absorption and for the majority of diffusion processes. It occurs when a given component from one phase is transformed to a second phase, and nothing comes back to the first one. The component that does not participate in the transformation between phases is termed indifferent.

The one-directional diffusion of component A in the unmoving component B occurs both in nature and in technical praxis – a very common example is the evaporation of liquids into inert gases. Component B, which does not participate in the diffusion, is referred to as inert.

$$n_B = 0 \tag{7.28}$$

For diffusion through a thick layer, for example with diffusion in a circular tube where there is a section with different partial pressures at either end, the equation below applies:

$$n_A = \frac{D_{AB}\, p}{R\, T\, z} \ln \frac{p_{B2}}{p_{B1}} \tag{7.29}$$

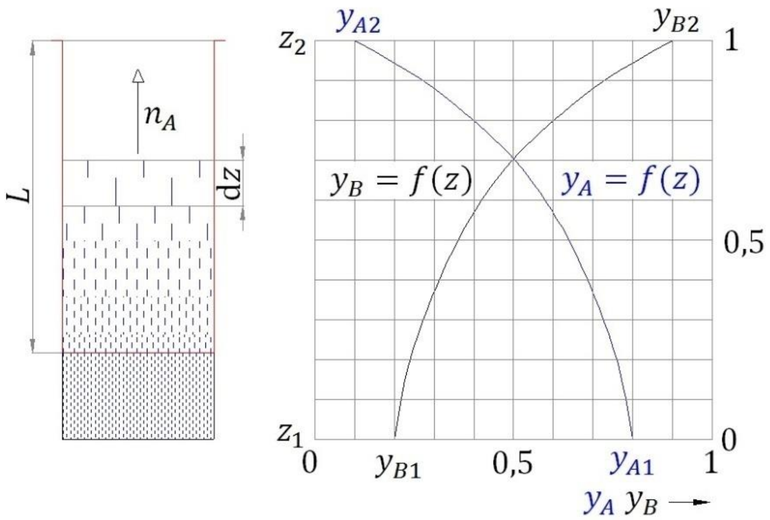


Fig. 7.8 One-directional diffusion [6]

- ***two-directional diffusion***

With two-directional diffusion (characteristic for rectification, for example), one component comes out of the first phase (liquid) into the second (gas) and vice versa. With two-directional material transfers, diffusion is usually equimolecular, because the amount of component A removed from a certain place is replaced in this place by a molecularly equivalent amount of material B, diffusing in the opposite direction.

The receptacle below has a partition so that the volumes on both sides are the same. In the partition is a tube sealed at both ends. Two pure gases are separated from each other in the receptacle's compartments. The overall pressure and temperature in the receptacle are equal, so in accordance with Avogadro's law, the number of molecules is also the same.

If both sections are opened simultaneously, there occurs a phenomenon that is termed two-directional or equimolecular diffusion. The amount of material A diffusing from one material to the second is equal to the amount of material B which travels in the opposite direction.

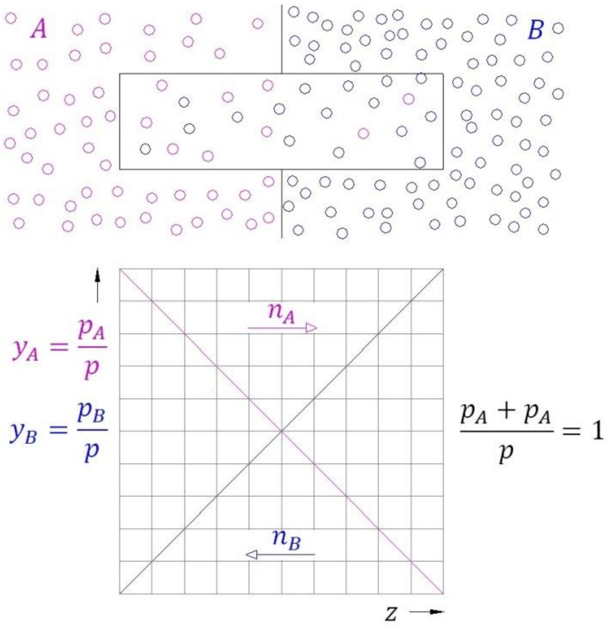


Fig. 7.9 Two-directional diffusion [6]

For equimolecular diffusion is valid:

$$n_A + n_B = 0 \tag{7.30}$$

For equimolecular diffusion in the gas phase is valid:

$$n_B = \frac{D_{AB}}{R\,T\,(z_2 - z_1)}(p_{A1} - p_{A2}) \tag{7.31}$$

In the stationary phase, transport of material is a phenomenon of molecular dimensions and occurs as the result of the motion state of the molecules.

The transfer of a material by molecular diffusion can be divided into:

- ***concentration diffusion*** – the driving force of the process is the concentration gradient or more generally, the chemical potential gradient. This mechanism of transfer of mass is the most widespread. Flow density is expressed by Fick´s 1st law;
- ***thermal diffusion*** – the driving force of thermal diffusion is the heat gradient. In the non-isothermal field of binary mixtures, thermal diffusion occurs such that the molecules of one component will move to the area with a higher temperature level, while the molecules of the second component will move to the area with a lower temperature level. Some apparatuses for the separation of isotopes work on the principle of the so-called Soret's phenomenon;
- ***pressure diffusion*** – the driving force of pressure diffusion is the pressure gradient. The effects of pressure diffusion are employed for the separation of the components of a mixture, e.g. in certain types of high-speed centrifuges. It has no great significance from the standpoint of industrial application;
- ***diffusion effect of an external force field*** of another type than gravitational. Such a field may be created by electricity or electromagnetics. This principle can be applied in cases where the external force field acts with different effects on the individual components. A standard case is the diffusion of ions in electrolytes.

MECHANISMS OF MASS TRANSFER BY FLOWING

Diffusion flow (convective diffusion) occurs in turbulent flows of gases and liquids. It is conditioned by the movement of a liquid as a whole, therefore by volume flow. The solution of problems of mass transport represents simultaneously the solution of equations of transfer of momentum and mass.

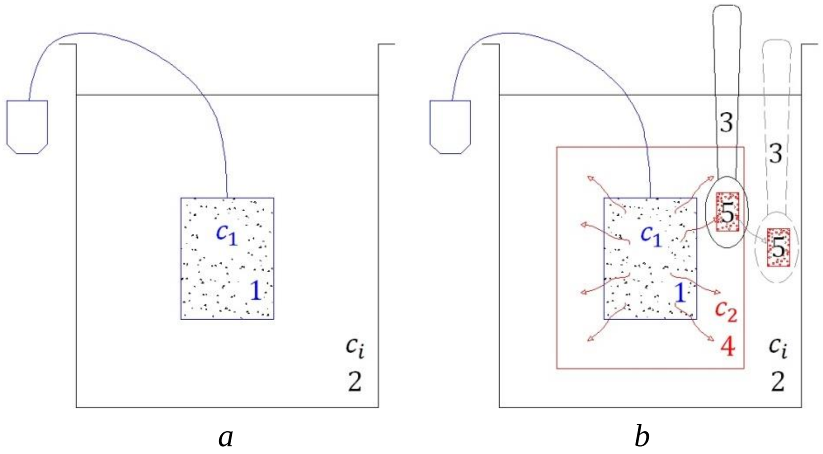


Fig. 7.10. Diffusion process in brewing tea with mixing is a typical case of molecular diffusion with the application of convective and conductive mechanisms [6]:
a – concentration of tea at the moment of immersing the teabag in water,
b – distribution of the concentration field in the water after a certain period of time,
1 – teabag with concentration c_1, 2 – water, 3 – spoon

The transport of material in a moving phase depends on the character of the flow phase, while the resistance to it varies according to the type of flow.

- ***laminar flow***

Such diffusion occurs when the Reynolds number values are small. In laminar flow, the lines of flow of liquid are parallel to the phase interface. Since the transport of the material is perpendicular to the phase interface, it is then perpendicular to the flow path. Under such conditions the flow phase does not help displace the material in the direction of the phase interface, and so does not speed up the exchange of materials between the phases. The transport of material is carried out from one line of flow to another as an event of molecular dimensions. Its speed is dependent on the concentration gradient and the size of the resistance, defined similarly as the resistance with molecular diffusion in the stationary phase. The same relations as for molecular diffusion apply here.

Figure 7.11 illustrates such a situation. Two phases (1) and (2) are in mutual contact. Phase (2) is stationary, and phase (1) flows across it in a horizontal direction. At the point of contact of the phases, the flow speed of phase (1) is zero, but in the direction from the phase interface it increases to the value u. Let phase (1) flow so fast that the character of flowing is laminar. Then it becomes possible to separate this phase into imaginary layers and from them take the imaginary control volumes in which the molecules of this phase are located. So if the flow regime is laminar, then the control volumes move at a speed (3) corresponding to the given layer in a horizontal direction. The transfer of the material from layer to layer in the direction of the fall of the concentration gradient is only molecular (4).

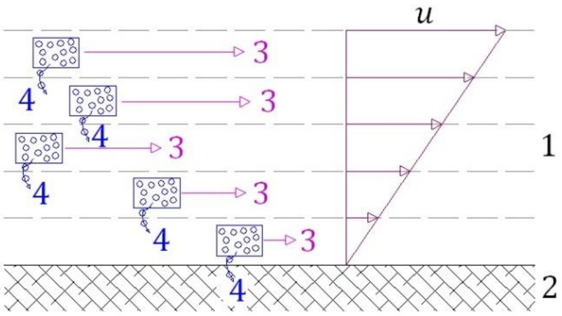


Fig. 7.11. Diffusion in a laminar flowing liquid [6]:
1 – layer of laminar flowing liquid, 2 – layer of stationary liquid,
3 – direction of flowing of liquid in individual imaginary layers,
4 – molecules diffusing to the interphase interface from imaginary control volumes

- ***turbulent flow***

Here the transport of material and the equalizing of concentration differences are primarily the result of mechanical mixing of the elemental phase volumes. The share of molecular diffusion in overall transport is negligible. The speed of the equalizing of the concentration differences in the turbulent flow depends on the intensity of the mixing phase, and so on the size of the Reynolds number. The greater the flow turbulence, the less is the resistance against transport. The speed of the material transport in the phases moving by turbulent flow is much greater than the speed of material transport in the stationary phases or in the phases moving laminarly along the phase interface.

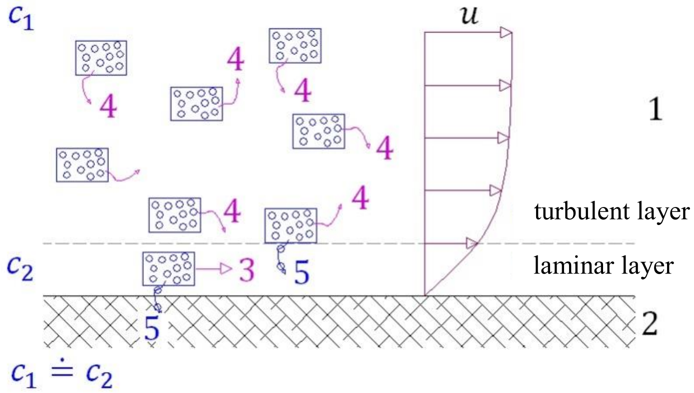


Fig. 7.12. Diffusion in turbulently flowing liquid [6]:
1 – layer of flowing liquid, 2 – layer of stationary liquid 3 – direction of liquid flow in the laminar layer, 4 – direction of liquid flow with control volume in the turbulent layer,
5 – molecules diffusing to the interphase interface from the imaginary control volumes

Figure 7.12 illustrates such a situation. Two phases (1) and (2) are in mutual contact. Phase (2) is stationary and phase (1) flows over it in a horizontal direction. At the point of contact of the phases, the flow speed of phase (1) is zero, increasing from the phase interface to value u. In the immediate vicinity of the phase interface is created a layer of laminarly flowing liquid. In this stage, the control volume again moves only in a horizontal direction (3) and the transport of material in the direction of the phase interface takes place on a molecular level (5). Above it is situated the layer of turbulently flowing liquid. The control volumes in it move along curve lines (4) – so intensive mixing occurs here. The control volume which comes to the top of the laminar layer allows the transport of the material on a molecular level (5) to the laminar layer.

The transport of material in the phase occurs not only by the creation of a concentration gradient by two phases coming into contact, but also by the effect of, for example, pressure or thermal gradients.

- ***Forced convection*** – the component or mixture is transported by convection (volume) flow, which is caused by a pump or fan, for example,
- ***Natural convection*** – in this case, the transfer of mass is again carried out by volume flow, but the driving force is the density gradient in the liquid.

The transfer of material in turbulent flowing phases is much faster than the transfer of material by molecular diffusion because, as a result of the turbulence, the material as a whole is relocated in a direction towards the phase interface of the liquid, and with it the material too is transferred through the phase interface by convection.

In the transfer of material through the phase interface, in addition to diffusion and convection mechanisms, phase equilibrium always applies. The expression of phase equilibrium comes from the second law of thermodynamics.

According to the type of phases through which the transfer of material occurs, they can be divided into:

- ***gas - liquid*** (rectification, absorption, air humidification and the like),
- ***liquid - liquid*** (liquid extraction),
- ***gas - solid phase*** (adsorption from gases, the drying of solid materials),
- ***liquid - solid phase*** (leaching, liquid adsorption, and the like).

According to the course and arrangement, diffusion transfers can be divided into:

- ***stationary***- continuous phenomena (e.g. rectification, absorption),
- ***non-stationary*** – discontinuous phenomena, materials come into contact only once. If the discontinuous process is used more than once, these are step processes (e.g., stepped liquid extraction).

With stationary phenomena, the phases may be categorized as:

- ***parallel flow,***
- ***counterflow,***
- ***crossflow.***

In the examination of these processes, conductive (molecular) or convective (flowing) types of material transfer must be considered.

CONVECTIVE TRANSFER OF MASS IN THE VICINITY OF PHASE INTERFACES – FILM THEORY

According to film theory, diffusion processes assume that the transfer of material through phase interfaces is so fast that in the immediate vicinity of the phase interface the concentration of material achieves an almost instant equilibrium value. This assumption is based on the concept that the phase interface presents no or negligible resistance to the transfer of material.

The emergence of concentration differences of the component in the phases within a phase interface is caused by the fact that the concentration of the component transferred between the phases is in equilibrium and so depends only on the thermal-dynamic state of the system. The concentration differences in the phases in a system are compensated by the transport of the substance in the direction of decreasing concentration, i.e. by moving it from places where the concentration of the component is higher to places with a lower concentration. The result of the attempts of a system to equalize the concentration gradients is the transport of the material in one phase in the direction of the phase interface. The equilibrium composition of the phase interface is disturbed by the transporting of the material between the phases, while at the same time the transfer of the material through the phase interface is continually renewed. The result of these events is the exchange of material between the phases, during which in a steady state the amount of material in one phase transferred to the phase interface equals the amount of this material transferred through the phase interface and the amount of material in the second phase moving towards the phase interface.

Film theory consists in the assumption that there exists an unchanging layer of thickness δ_D in the phase interface, in which transport of the mass by molecular diffusion occurs. The thickness of the layer is such that it specifically expresses the total resistance against the mass transfer between the phase and the flowing liquid. The thickness of this layer depends on the intensity of turbulence in the phases, therefore it depends on the Reynolds number. In a steady state, an equal amount of material must advance through the laminar film in a molecular way as is moved by convection from the core of the flow to the film interface.

In figure 7.13 is shown an example of one-directional diffusion of material A from a liquid to a flow gas flowing parallel to the surface. According to film theory, the whole diffusion resistance that component A must overcome before it gets from the surface of the liquid to the core of the flow is concentrated in a film of thickness δ directly over the interphase interface. It is therefore a fictive value that represents the thickness of a stagnant layer B of such diffusion resistance in a molecular way, like the real diffusion resistance of the convection and molecular transport of material.

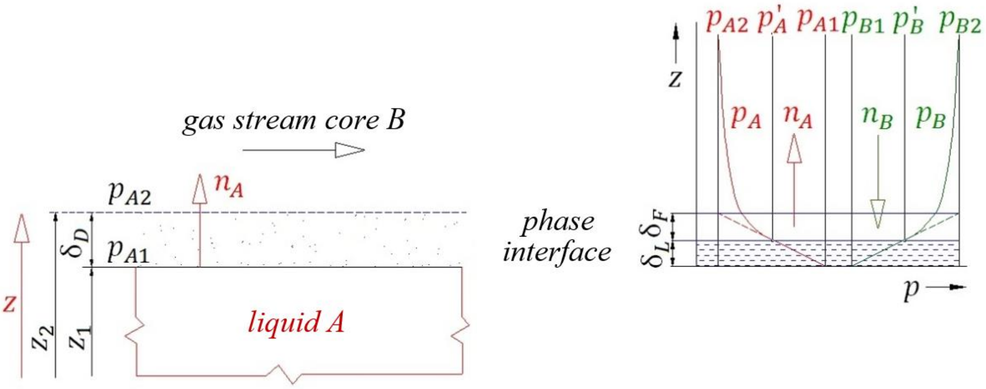


Fig. 7.13. Film theory – convection transfer of material in the vicinity of phase interface [6]

For an equimolecular exchange of material, there applies the relation:

$$n_A = \frac{D_{AB}}{R\,T\,\delta_D}(p_{A1} - p_{A2}) \tag{7.32}$$

where

D_{AB} – diffusion coefficient (diffusivity) of component A in the binary mixture A+B (a material parameter which depends on both components is a function of temperature and pressure in the system, mostly achieved empirically) $(\mathrm{m^2.s^{-1}})$

p_{A1} – partial pressure of component A in the interphase interface (Pa)

p_{A2} – partial pressure of component A in the main phase flow (Pa)

δ_D – thickness of diffusion film (m)

Thickness of diffusion film

$$\delta_D = \delta_L + \delta_F \tag{7.33}$$

where

δ_L – thickness of laminar film (m)

δ_F – thickness of thin fictive film that would present the transfer of a material with the same resistance as a turbulent core presents (m)

In the equation (7.32) all the quantities are known. The most complex act is to determine the thickness of the diffusion film. For this are used the criterion equations gained by experiment.

DRIVING FORCE OF DIFFUSION PROCESSES

On the basis of the above-mentioned concepts, it can be stated that the speed of the diffusion processes, measured by the amount of material transferred from one phase to the other through the unit area of the phase interface per unit of time, is dependent on the speed of its transport in the contacting phases

The transport of the material depends on the driving force and the resistance against its transfer from a point of higher concentration to a point of lower concentration.

In general, the driving force for the transfer of material from one point to another in the phase is the concentration difference at these points. The exchange of the material between the phases will be faster in dependence on the size of the difference in the material concentration in the phase and the phase interface, in other words the more distant the system is from the equilibrium state.

The most frequent example of molecular transport is concentration diffusion, where the driving force for the transfer of mass is the concentration gradient.

Flow density is expressed by Fick's 1st law:

$$\bar{J_A} = -D_{AB}\,\nabla x_A\,\rho \tag{7.34}$$

where

$\bar{J_A}$ – flow density of component A by molecular diffusion (a vector quantity, which is collinear to its concentration gradient, constant concentration areas are perpendicular to the direction of flow intensity) $(\mathrm{kg_A.m^{-2}.s^{-1}})$

ρ – the density of the mixture at a given point in the coordinate system $(\mathrm{kg.m^{-2}.s^{-1}})$

LIST OF SYMBOLS

c – mole-volume concentration $(\mathrm{mol.m^{-3}})$
c_i – mole-volume concentration of component i $(\mathrm{mol.m^{-3}})$
$c_{i,e}$ – concentration of component i (1)
i – component (1)
$\overline{J_A}$ – flow density of component A by molecular diffusion (a vector quantity, it is collinear with its concentration gradient, constant concentration areas are perpendicular to the direction of flow intensity) $(\mathrm{kg_A.m^{-2}.s^{-1}})$
m_i – mass of component i (kg)
n_i – mole amount of component i (mol)
p – pressure (Pa)
p_i – partial pressure of component i (Pa)
p_i^0 – pressure of saturated vapours of pure component i (Pa)
p_{ok} – ambient pressure (Pa)
u – speed $(\mathrm{m.s^{-1}})$
u_i – mean speed of movement of the molecules of component i $(\mathrm{m.s^{-1}})$
v – specific volume $(\mathrm{m^3.kg^{-1}})$
x_i – relative mole component of component i in liquid state (1)
y_i – relative mole component of component i in gas state (1)
z – length (m)
A – integration constant (1)
B – integration constant (K)
C_i – concentration of component i (1)
D_{AB} – diffusion coefficient (diffusivity) of component A in binary mixture A+B $(\mathrm{m^2.s^{-1}})$
H_i – Henry constant of component i (Pa)
K_c – equilibrium constant (1)
K_i^0 – equilibrium distribution coefficient (1)
R – universal gas co-instance $(\mathrm{J.mol^{-1}.K^{-1}})$
T – temperature (K)
T_{ok} – temperature of surroundings (K)
T_v – boiling point (K)
V – volume $(\mathrm{m^3})$
X_i – absolute mole component of component i in liquid state (1)
Y_i – absolute mole component of component i in gas state (1)
α_{AB} – relative volatility of components A and B (1)
β – proportionality coefficient (1)
δ_D – thickness of diffusion film (m)
δ_F – thickness of thin fictive film that would present the transfer of a material with the same resistance as a turbulent core presents (m)
δ_L – thickness of laminar film (m)
$\mu_i^{(g)}$ – chemical potential of i component in gas phase $(\mathrm{J.mol^{-1}})$

$\mu_i^{(l)}$	–	chemical potential of i component in liquid phase	$(\mathrm{J.mol^{-1}})$
ρ	–	density of mixture at a given point in a coordinate system	$(\mathrm{kg.m^{-2}.s^{-1}})$
ρ_i	–	density of component i	$(\mathrm{kg.m^{-3}})$
$\Delta_{sol}h_{T,i}$	–	differential dissolution enthalpy of component i	$(\mathrm{J.mol^{-1}})$

8 DISTILLATION

Distillation is a diffusion process that is used for separating liquid mixtures. Separation of the components of liquid mixtures takes place on the basis of the differing boiling points of the individual ingredients, where the liquid mixtures are heated such that the individual materials are separated by evaporation until the non-volatile part remains on the bottom of the equipment and the cooled vapours are condensed into a distillate.

Distillation is one of the most widespread diffusion processes, by which materials making up liquid solutions that have different vapour tensions at the same temperature or with equal pressure but different boiling points can be separated. This does not apply to liquids forming so-called azeotropic mixtures. With non-azeotropic mixtures, after the partial evaporation of the liquid, the vapours are always richer than the liquid in some component, usually the component with the lower boiling point.

By separating and condensing the vapours emerging from the liquid mixture, a liquid richer in one or the other component is obtained, in dependence on the composition and number of components in the initial mixture. The liquid obtained is called a distillate.

SIMPLE DISTILLATION

Simple distillation is the process by which there occurs single-stage evaporation combined with consequent condensation. It is divided into two types:

- ***equilibrium distillation*** – the composition of the distillate and the liquid in the distillation drum is constant and corresponds to the equilibrium make-up,
- ***differential distillation*** – the composition of the liquid in the distillation drum, and the composition of the equilibrium vapours, is constantly changing.

In the following part, it will be assumed that an ideal mixture, or a real mixture with behaviour similar to the ideal, is referred to.

MATERAL BALANCE OF CONTINUOUS DISTILLATION OF BINARY MIXTURES

With continuous distillation, the following are added to the distillation equipment:

- ***solution*** – amount of solution $\dot{F}$ $(\mathrm{mol.\,s^{-1}})$,
  – mole component of the more volatile component in the solution x_F.

From the equipment is removed:

- ***distillate*** – amount of distillate $\dot{V}$ $(\mathrm{mol.\,s^{-1}})$,
  – mole component of the more volatile component in the distillate x_V.
- ***distillation remainder*** – amount of distillation remainder $\dot{L}$ $(\mathrm{mol.\,s^{-1}})$,
  – mole component of the more volatile component in the distillation remainder x_L.

If the distillate has an equilibrium composition from the standpoint of the distillation remainder, the mole fraction of the more volatile component in the distillate will be designated as y_V.

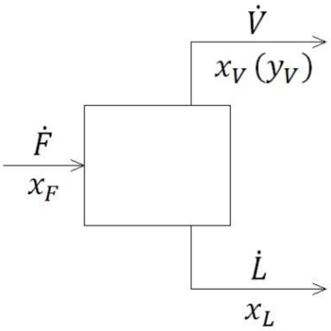


Fig. 8.1 Basic diagram of continuous distillation of binary mixtures [6]

The material balance of continuous distillation of a binary mixture will be:

$$\dot{F} = \dot{V} + \dot{L} \tag{8.1}$$

$$\dot{F}\, x_F = \dot{V}\, x_V + \dot{L}\, x_L \tag{8.2}$$

EQUILIBRIUM DISTILLATION OF BINARY MIXTURES

Figure 8.2 shows an equilibrium distillation diagram. In a continuous process, the solution is put into a heat exchanger (1), where it is heated and partially evaporated. The mixture of vapour and liquid then continues to the separator (2), from where the vapours are removed through the condenser (3) as a distillate, and the liquid through a cooler as the remainder (4).

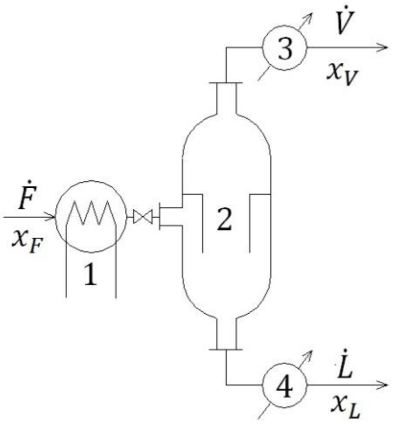


Fig. 8.2. Diagram of equilibrium distillation [6]:
1 – heat exchanger, 2 – separator, 3 – condenser, 4 – cooler

Since the vapour and the liquid are in contact for a determined time after exiting from the exchanger, equilibrium continues between them. The relation between the components of the distillate and the remainder is then given by the equilibrium curve of diagram $y - x$ (Fig. 8.3) or diagram $T - x, y$ (Fig. 8.4).

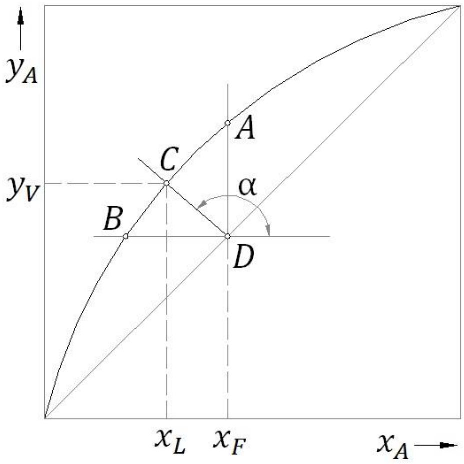


Fig. 8.3. Ratio influence $\dot{L}/\dot{V}$ on composition of distillate at equilibrium distillation $\dot{L}/\dot{V} = -tg\,\alpha$ [6]

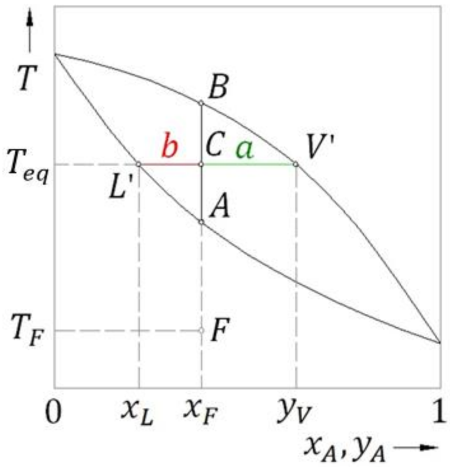


Fig. 8.4. Equilibrium distillation, representation in $T - x, y$ diagram [6]

The equilibrium curve equation is:

$$y_V = f(x_L) \tag{8.3}$$

By combining the material balance equations, the following form is obtained:

$$\frac{\dot{L}}{\dot{V}} = \frac{y_V - x_F}{x_F - x_L} \tag{8.4}$$

From this it follows that it is possible to change the composition of a distillate and the remainder by a change in the relation of the flow of the distillation remainder and the distillate.

If the flow of the distillate is infinitely small, then:

$$x_F - x_L = 0 \ \rightarrow \ x_F = x_L \tag{8.5}$$

and the composition of the distillate is given by point A on the equilibrium curve.

If, however, an infinitely small amount of the remainder is removed, the composition of the distillate equals the composition of the raw material, and the composition of the remainder is given by point B.
In real conditions, however, the amount of the distillate of the remainder is finite, and so its composition is given by point C.

In diagram $T - x, y$ the feed is shown by point F corresponding to temperature T_F and the concentration of the more volatile component x_F. This is heated to form the vapor-liquid mixture given by point C. Therefore, the point must lie between the boiling and condensation curves (between points A and B). This mixture is then divided in a separator into the liquid remainder (L') with the mole fraction of the more volatile component x_L and the vapours of the distillate (V') with mole fraction y_V and with equilibrium temperature T_{eq}.
By using the leverage rule, for the ratio of lines a, b, it is valid:

$$\frac{a}{b} = \frac{\dot{L}}{\dot{V}} \tag{8.6}$$

DIFFERENTIAL DISTILLATION

In figure 8.5 is portrayed a differential distillation diagram. Differential distillation is a discontinuous process. The distillation vessel (1) is filled with fresh solution. This is brought to the boil with either a vapour tube or a duplicator (2) in which there is steam. Part of the solution is distilled, with the distillate condensing in the condenser (3) and being caught in a container (4). After the completion of distillation, the remainder stays in the vessel with a lower concentration of the more volatile component than in the original solution.
Differential distillation occurs when, in a very short (differential) time interval, a differentially small amount of vapours leaves the fluid phase, and these vapours at that exact moment have a composition in equilibrium with the fluid. However, the vapours are richer in the more volatile component - the less its concentration in the fluid, the more the equilibrium is disturbed. The vapours which will leave in the next instant already have a smaller content of the more volatile component corresponding to the new equilibrium state, with the fluid poorer in the more volatile component.

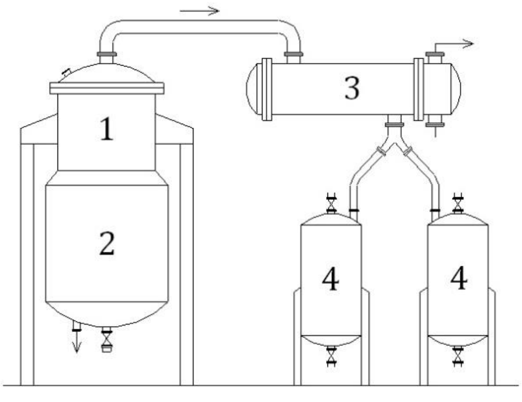


Fig. 8.5. Equipment for differential distillation [6]:
1 – distillation boiler, 2 – heating duplicator, 3 – condenser, 4 – condensate container

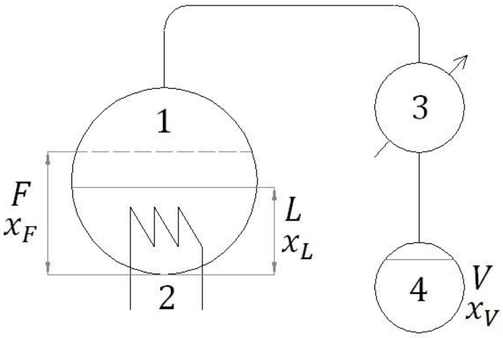


Fig. 8.6. Differential distillation diagram [6]:
1 – distillation boiler, 2 – heating duplicator, 3 – cooler, 4 – condensate container

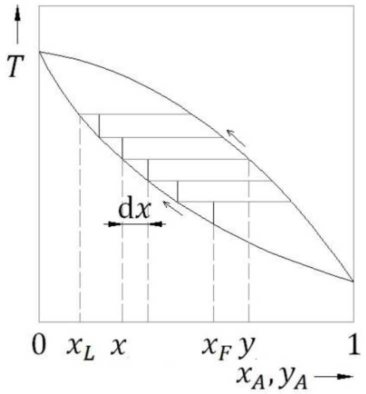


Fig. 8.7. Differential distillation, depicted in a $T - x, y$ *diagram [6]*

Therefore, in differential distillation the equilibrium is constantly being disturbed, with a continual decrease in the content of the more volatile component in the distillate and in the remainder. As a result of this, the temperature of the vapours and the fluids increases during the distillation.

Diagram $T - x, y$ allows the tracking of temperature changes during differential distillation. From this viewpoint, differential distillation can be pictured as a large number of mutually connected equilibrium distillations, with the mole fraction of the more volatile component changing by $\mathrm{d}x$ at each stage.

Since the composition of the distillate changes steadily, it can be captured continuously to obtain different distillate compositions. This is used advantageously with the division of multi-component mixtures, if they have sufficiently different boiling temperatures. For example, when dividing a mixture with three components, it is possible to remove from the distillate two fractions, one richer in component A and the second richer in component Bn, while the remainder, rich in component $C,$ remains in the boiler..

LIST OF SYMBOLS

x	–	mole fraction in fluid state	(1)
x_V	–	mole fraction of more volatile component in distillate in fluid state	(1)
x_F	–	mole fraction of more volatile component in solution in fluid state	(1)

x_L – mole of more volatile component in distillate remainder in fluid state (1)

y – mole fraction in vapour state (1)

y_V – mole fraction of more volatile component in distillate in vapour state (1)

$\dot{F}$ – mole flow of solution (feed) $(\mathrm{mol.\,s^{-1}})$

$\dot{L}$ – mole flow of solution $(\mathrm{mol.\,s^{-1}})$

T – temperature (K)

T_{eq} – equilibrium temperature (K)

T_F – temperature of feed (K)

$\dot{V}$ – mole flow of distillate $(\mathrm{mol.\,s^{-1}})$

9 RECTIFICATION

Simple distillation is a rather imperfect way of evaporating fluid mixtures and may only be successfully used where there is a great difference in the boiling points of the components. More successful evaporation may be achieved by repeated simple distillation, referred to as rectification, which can be considered as multiple partial evaporation and condensation. Rectification is thus the process of multiple distillation and condensation with the direct transfer of heat from the vapour to the fluid and the mutual transfer of a material between a vapour and a fluid.

A diagram of the simplest method of repeat continuous distillation of a binary mixture is shown in figure 9.1. Raw material F (the so-called feed) is put into a boiler, where it is distilled. Distillate V_1 containing a more volatile component is piped into a second boiler. The distillate from the second boiler V_2 is again distilled until it gains a sufficiently concentrated distillate V.

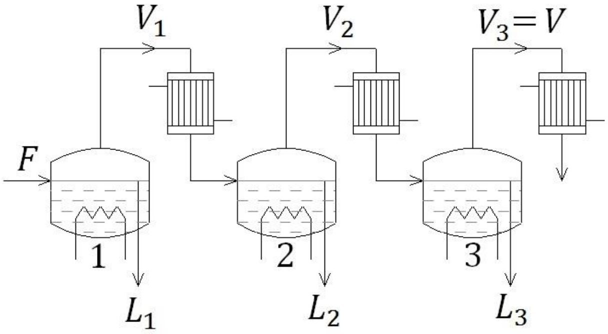


Fig. 9.1. Diagram of multiple continuous distillation without the use of residue [6]

With this procedure, if a significantly concentrated distillate is the end product, there occurs a great amount of residue $L_1 + L_2 + L_3$, which contains an even more volatile component. For the process to be as efficient as possible, it is advisable to distill the residue also. This is achieved by counter flow piping of the residue from boiler 3 to boiler 2 and from there to boiler 1 (Fig. 9.2).

If the residue from the first boiler still contains a large quantity of the more volatile component, this component is again distilled in one or more subordinate boilers (1', 2'). The distillate from these boilers is piped back into the preceding boiler. The result is distillate V containing, according to the character of the original mixture, a more volatile component and residue L, containing significantly less of the volatile component. It is clear that the more boilers used, the sharper the division of the mixture will be.

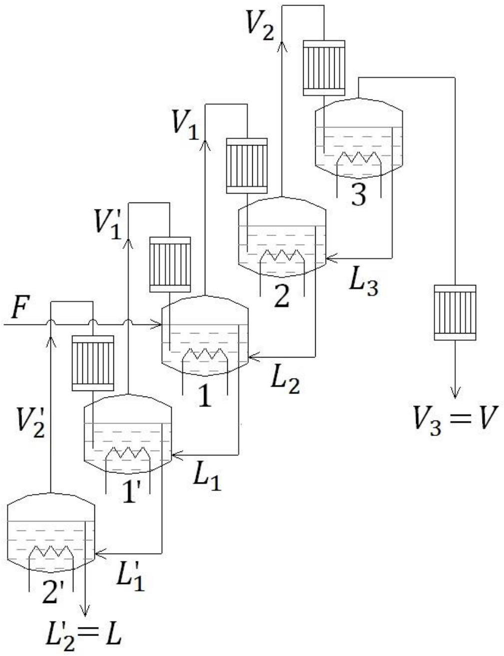


Fig. 9.2. Diagram of multiple continuous distillation with the use of residues [6]

Rectification theory is based on the concept of the existence of a theoretic tray. It is a tray that works such that the vapour leaving it is in equilibrium with the liquid flowing from it. The introduction of this concept is important from the standpoint of simplifying the calculation of the rectification column.

The feed tray divides the column into two parts:

- ***the enriching part***
  - is located above the feed tray and serves to enrich the distillate vapours with the more volatile component,
- ***the diminishing part***
  - is located below the feed tray and serves to remove the more volatile component from the residue.

Trays in the column are always numbered downwards:

- ***the general enrichment tray***
  - is designated as the n^{th} tray from the feed tray,
  - flow of the vapours leaving is $\dot{V}_n$,
  - flow of the fluid (internal reverse flow) $\dot{L}_n$,
- ***the general diminishment tray***
  - is designated as the m^{th} tray from the bottom of the column.

And the designation of the other quantities is as follows:

- ***distillate flow*** ($\dot{V}$),
- ***feed*** ($\dot{F}$),
- ***distillation residue*** ($\dot{L}$),
- ***external reverse flow*** ($\dot{L}_D$).

In the calculation, all the mole fractions relate to the more volatile component, therefore to A, and to simplify the designation, this index is not stated.

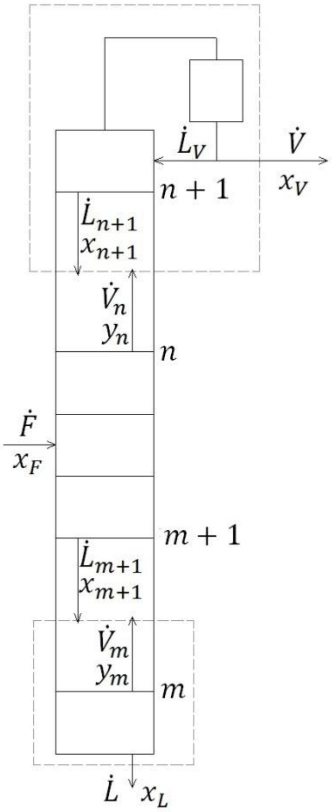


Fig. 9.3. Basic diagram for deriving a continuous rectification equation [6]

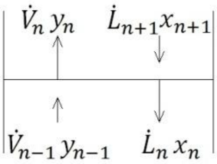


Fig. 9.4. Flow diagram of nth rectification tray [6]

In the nth tray in the enrichment part (Fig. 9.4), vapours with the mole fraction of the more volatile part y_{n-1} come from the lower tray $\dot{V}_{n-1}$ $(\mathrm{mol.\,s^{-1}})$ and from the $n+1$ tray $\dot{L}_{n+1}$ $(\mathrm{mol.\,s^{-1}})$ fluids of composition x_{n+1}. $\dot{V}_n$vapours and $\dot{L}_n$ fluids of equilibrium composition y_n and x_n leave. The total balance of the tray is:

$$\dot{V}_{n-1} + \dot{L}_{n+1} = \dot{V}_n + \dot{L}_n \tag{9.1}$$

Or for the more volatile component:

$$\dot{V}_{n-1}\, y_{n-1} + \dot{L}_{n+1}\, x_{n+1} = \dot{V}_n\, y_n + \dot{L}_n\, x_n \tag{9.2}$$

The material balance for the enriching part of the column, which is illustrated in figure 9.3 in the outlined area in the upper part of the column, can be written similarly. $\dot{V}_n$ $(\mathrm{kmol.\,h^{-1}})$ vapours come into it, $\dot{V}$ $(\mathrm{mol.\,s^{-1}})$ distillate leaves, and $\dot{L}_{n+1}$ $(\mathrm{mol.\,s^{-1}})$$is\ an$ internal reverse flow. Then the whole material balance is:

$$\dot{V}_n = \dot{L}_{n+1} + \dot{V} \tag{9.3}$$

or for the more volatile component:

$$\dot{V}_n\, y_n = \dot{L}_{n+1}\, x_{n+1} + \dot{V}\, x_V \tag{9.4}$$

If the reflux concept is introduced and defined by the equation:

$$R = \frac{\dot{L}_{n+1}}{\dot{V}} = \frac{\dot{L}_V}{\dot{V}} \tag{9.5}$$

By modification of these equations is given the form:

$$y_n = \frac{R}{R+1}\, x_{n+1} + \frac{1}{R+1}\, x_V \tag{9.6}$$

Similarly, for the diminishing part of the column, which is illustrated by the outlined area in the lower part of figure 9.3, the following equation can be written:

$$\dot{L}_{m+1} = \dot{V}_m + \dot{L} \tag{9.7}$$

or for the more volatile component:

$$\dot{L}_{m+1}\, x_{m+1} = \dot{V}_m\, y_m + \dot{L}\, x_L \tag{9.8}$$

By substituting and modifying the equations is obtained the form:

$$y_m = \frac{\dot{L}_{m+1}}{\dot{L}_{m+1} - \dot{L}}\, x_{m+1} + \frac{\dot{L}}{\dot{L}_{m+1} - \dot{L}}\, x_L \tag{9.9}$$

Equations (9.6) and (9.9) show the dependence of the composition of the fluid fed into the tray and of the vapour rising from the tray in the enriching or diminishing part of the column. Their graphic depiction in diagram $x - y$ is referred to as the working line of the column because they characterize the working conditions in a certain part of the column.

GRAPHIC CALCULATION OF THE NUMBER OF THEORETIC TRAYS

Since the fluid in the theoretic tray is in equilibrium with the vapours, the relation between the composition of the vapour coming onto the tray and the fluid leaving the tray is given by the individual points of the equilibrium curve. The relation of the composition of the vapour leaving the tray and of the reverse flow coming into the tray is given by the working line for the relevant area of the rectification column. On the basis of these relations, the graphic calculation of theoretic trays according to McCabe – Thiele is derived.

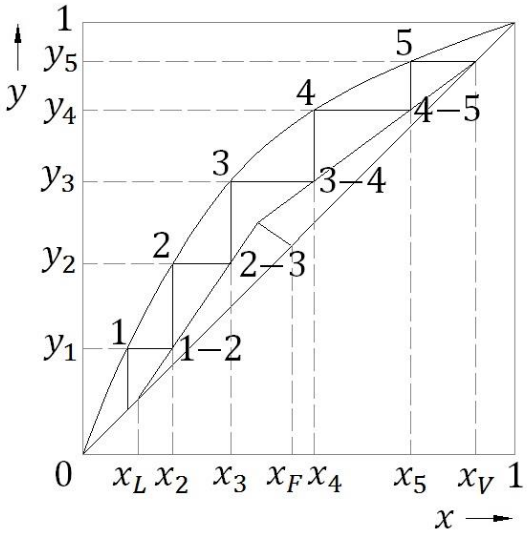


Fig. 9.5. Graphic calculation of the number of theoretic trays according to McCabe – Thiele [6]

- the intersection of the enriched straight line and the diagonal gives the mole fraction of the more volatile component in the reverse flow x_V and the mole fraction of the more volatile component in the vapours rising out of the top tray $y_5 = x_V$,
- the vapour rising from the tray is in equilibrium with the fluid running off from the tray which has the mole fraction of the more volatile component x_5, which determines point 5 on the equilibrium curve; value x_5 corresponds to the mole fraction of the more volatile component in the vapours from the lower tray y_4 (point $4-5$ on the enrichment curve),
- this vapour is in equilibrium with the fluid running off from the fourth tray with the mole fraction of the more volatile component x_4, to which corresponds point 4 on the equilibrium curve. Value x_4 corresponds to the mole fraction of the more volatile component in the vapours from tray y_3 immediately below y_3 (point $3-4$ on the enrichment curve).

This method provides the values of the mole fractions of the most volatile component in vapours and fluids in the individual trays.

This method also allows the identification of the number of theoretical trays. Since one right-angle step represents the transmission from one tray to the next, so the number of such steps gives the number of theoretical trays. A right-angle step above the intersection of the working lines means a movement from the enriching to the diminishing part of the column, and therefore indicates the feeder tray.

It carries on to the diminishing straight line. The last step finishes at the intersection of the diminishing straight line with the diagonal, which means at the mole fraction x_w and gives the ratios in the bottom of the column.

Therefore the column according to figure 9.5 has the number of theoretical trays $PTE = 5 - 1$ (bottom of the column) $= 4$.

THE ENTHALPY BALANCE OF A RECTIFICATION COLUMN

The heat diagram of a continuously working rectification column is seen in figure 9.6. The enthalpy balance constructed according to this scheme then has the form:

$$\dot{F}\, i_F + \dot{Q}_P = \dot{Q}_K + \dot{Q}_V + \dot{D}\, i_V + \dot{Q}_L + \dot{W}\, i_L + \dot{Q}_{st} \tag{9.10}$$

where

i_F – feeder enthalpy $(\mathrm{J.mol^{-1}})$
i_V – distillate enthalpy $(\mathrm{J.mol^{-1}})$
i_L – distillation residue enthalpy $(\mathrm{J.mol^{-1}})$
$\dot{Q}_P$ – heat for evaporating fluid into two columns (W)
$\dot{Q}_K$ – heat released by vapours in condenser (W)
$\dot{Q}_V$ – heat released in distillate cooler (W)
$\dot{Q}_L$ – heat released in distillation residue cooler (W)
$\dot{Q}_{st}$ – heat losses (W)

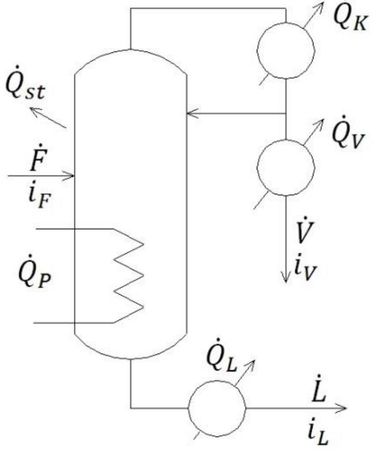


Fig. 9.6. Diagram of the heat balance of a rectification column [6]

APPARATUSES

The arrangement of the boilers as in figure 9.2 is very inefficient in terms of energy because each boiler needs its own heating and condensation, which increases operating expenses for heating and cooling the water.

Since the temperature is reduced in an upward direction in the boilers (because the distillate from the preceding degree contains more volatile components), the heat freed up by condensation of the vapours can be used to heat the fluid in the boiler situated above. It is done such that the vapours are fed directly into the liquid in the next boiler by the dispersing device.

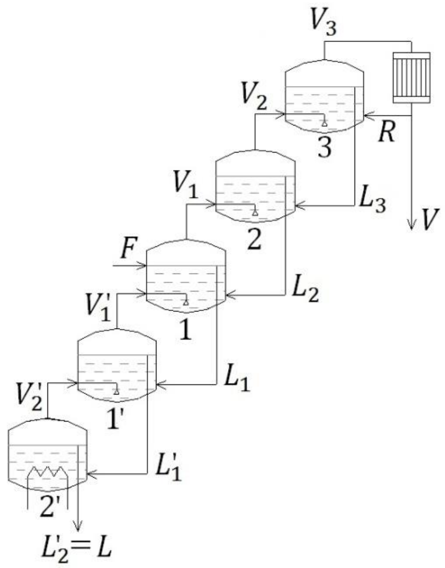


Fig. 9.7. Principle of rectification [6]

An amount of the less volatile component condenses from the vapours such that the temperature of the vapour equals the temperature of the fluid in the boiler (equilibrium is achieved). The released condensation heat simultaneously evaporates part of the more volatile fluid component in the boiler. This means a combination of heat transfer and substance transfer. So that the level of fluid and its concentration is maintained in the first boiler, part of the distillate must be fed back (R in figure 9.7). This part of the distillate is called reflux (reverse flow). Without it, the whole process would stop working because, after the condensing of a specific more volatile component, the temperature of the fed-in vapour and of the fluid in the first boiler would be equal. As a result, the concentration of the more volatile component would be in equilibrium even before the contact of the vapour and the fluid, and material transfer would not occur.

The principle of rectification in multiple boilers however requires unnecessarily complicated equipment. The same effect is achieved in a so-called rectification column. In this, boilers are replaced by trays assembled above each other in a cylindrical body. Each tray represents one boiler. The feed, ordinarily a mixture of fluid and vapour, is run in by pipes in a so-called feeder tray. The vapour rises through openings on the tray and at the head (top) of the column travels to the condenser through a pipe. One part of the condensate returns to the tower as reverse flow, while the other part is taken out as distillate. The reverse flow with the added fluid part of the feed is run to the bottom of the tower, where one part is evaporated and the other part flows out as distillation residue. The column base replaces one tray and corresponds to the last boiler. The vapours rising from the bottom of the column are directed by bubble-caps on the openings of the trays so that they bubble through the fluid on the trays, which is richer in the more volatile component as a result of the reverse flow, corresponding to the equilibrium between the fluid and the vapour. The temperature differences between the incoming vapour richer in the less volatile component and the fluid on the tray, richer in the more volatile component, causes an exchange of heat and material between the two flows. The surplus fluid from the tray flows through the overflow pipe, which at the same time functions as a hydraulic plug on the lower tray.

FILLER COLUMN

These are bodies of a cylindrical shape (Fig. 9.8) filled with small bodies of different types (Fig. 9.9a) disposed on grills. These filler bodies can be replaced by a compact filler (Fig. 9.9b). In the spaces between the diminishing and enriching parts is a device for distributing the feed.

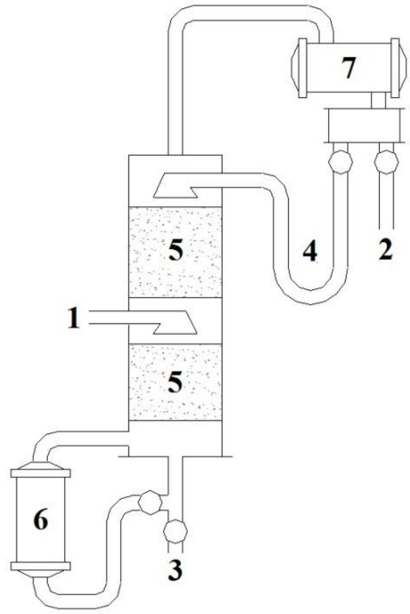


Fig. 9.8. Diagram of a filler column [6]:
1 – feed, 2 – distillate, 3 – distillate residue, 4 – reflux,
5 – filler, 6 – boiler, 7 – condenser


a *b*

Fig. 9.9. Small bodies and a compact rectification column filler [9]:
a – filler bodies, b – compact filler

The principle of a filler column consists in the surface contact of fluid and vapour. The reflux flows in a thin layer along the surface of the filler. Vapours of distilled fluid rise from the bottom against the reverse flow. On contact of the vapours with the fluid, the less volatile component of the vapours gradually condenses and at the same time the vapours become enriched by the more volatile component and vaporise from the reflux due to the freed condensation heat. So the vapours are regularly enriched in the filler columns.

The small filler bodies are of various shapes and are made of plastic, ceramic, or metal. Most frequently used are Raschig rings, Berl saddles and Lessing rings (Fig. 9.10).

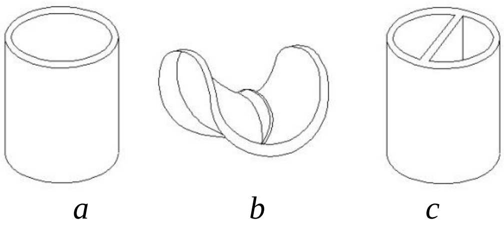


Fig. 9.10. Different shapes of filler columns [9]:
a – Raschig rings, b – Berl saddles, c – Lessing rings

The advantage of such columns is their simple construction and low pressure losses.

The disadvantage is, chiefly with low fluid flows, poor separation of the fluid to the full height of the filler, thus reducing the contact of the fluid and the vapour and reducing the column's efficiency.

TRAY COLUMNS

These are used most frequently, mostly due to their efficiency at a wide range of vapour speeds and great power per unit cross-section.

According to shape and function, columns can feature these:

- *bubble-cap trays,*
- *sieve trays,*
- *valve trays,*
- *tunnel trays.*

LIST OF SYMBOLS

i_F	–	feed enthalpy	$(\mathrm{J.\,mol^{-1}})$
i_L	–	distillation residue enthalpy	$(\mathrm{J.\,mol^{-1}})$
i_V	–	distillate enthalpy	$(\mathrm{J.\,mol^{-1}})$
m	–	designation of diminishing tray	(1)
n	–	designation of enriching tray	(1)
x	–	mole fraction in fluid state	(1)
x_F	–	mole fraction of more volatile component in fluid state	(1)
x_L	–	mole fraction of more volatile component in distillation residue in fluid state	(1)
x_V	–	mole fraction of more volatile component in distillate in fluid state	(1)
y	–	mole fraction in vapour state	(1)
F	–	amount of solution (feed)	(mol)
$\dot{F}$	–	mole flow of solution (feed)	$(\mathrm{mol.\,s^{-1}})$
L	–	amount of distillation residue	(mol)
$\dot{L}$	–	mole flow of distillation residue	$(\mathrm{mol.\,s^{-1}})$
L_i	–	distillation residue from i^{th} boiler	(mol)
$\dot{L}_n$	–	mole flow of fluid	$(\mathrm{mol.\,s^{-1}})$

$\dot{L}_V$ – external reflux $(\mathrm{mol.\,s^{-1}})$
$\dot{Q}_{st}$ – heat losses (W)
$\dot{Q}_K$ – heat given off by vapours in condenser (W)
$\dot{Q}_L$ – heat given off to distillation residue in cooler (W)
$\dot{Q}_P$ – heat for fluid evaporation at column bottom (W)
$\dot{Q}_V$ – heat given off to distillate in cooler (W)
R – reflux (1)
V – amount of distillate (mol)
$\dot{V}$ – amount of distillate $(\mathrm{mol.\,s^{-1}})$
V_i – distillate from i^{th} boiler (mol)
$\dot{V}_n$ – mole flow of vapours $(\mathrm{mol.\,s^{-1}})$

10 ABSORPTION

Absorption is the physical phenomenon by which gas is dissolved (absorbed) in a liquid. The separation of the components of a gas mixture by absorption is conditioned on their different solubility in a liquid solvent - absorbent. The quality of the separation of one or several components from the rest of the components of the gas mixture depends mostly on the choice of solvent. Accordingly, the following requirements must be met:

- the absorbent must dissolve the desired component adequately; liquids chemically similar to the dissolved component ordinarily have this property,
- it must be selective, which means that it should dissolve just the desired component; this property is called selectivity, and the efficiency of the separation of the absorbed component depends on it,
- the volatility of the dissolvent must be as low as possible in order to prevent the dirtying of the gas by its vapours, as well as the loss of the solvent; low absorbent volatility is also important due to the separation of the absorbed component from the solvent by desorption.

Absorption is by definition a diffusion process. The amount of material dissolved in the absorbent per unit of time, in other words the speed of absorption, is dependent on the concentration gradient of the absorbed component in phases. The rate of transport of this material in the gas phase in the direction of the phase interface, and in the liquid phase in the direction away from the phase interface, depends on this. This is an operation in which a one-directional material exchange through the phase interface takes place.

In the analysis of this process, it is assumed that one or more components of the gas are dissolved in the absorbent while the others remain undissolved. At the same time, it is assumed that the absorbent is a liquid with such a low saturated vapour pressure that its molecules do not pass through the phase interface. Such a system, made up of an absorbed component, an undissolved gas and the solvent has three degrees of freedom. This means that at a certain temperature and pressure, the composition of the liquid phase is clearly determined by the composition of the gas phase. This can be expressed mathematically by the relation

$$y = f(x)_{T,p} \tag{10.1}$$

where y, x are mole fractions of the absorption component in the gas or liquid phases in the system's equilibrium state. Graphic depiction of the function (10.1) is called the equilibrium curve. Its equation is usually written in the form

$$y = K\,x \tag{10.2}$$

where K is the equilibrium relation (distribution coefficient). It is not a constant, but it is a complex function which is generally dependent on temperature, pressure and the composition of the equilibrium phases. The principle of the calculation arises from the phase equilibrium between the liquid and the gas.

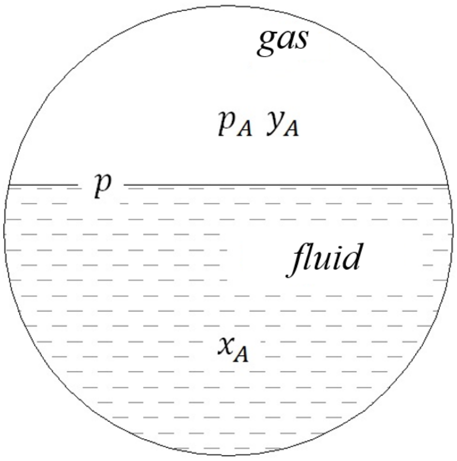


Fig. 10.1. Phase equilibrium [6]

If it includes an inert gas component A with concentration y_A, then at pressure p its partial pressure is given by the relation:

$$p_A = p\, y_A \tag{10.3}$$

Equilibrium between the gas and liquid phases is illustrated by Henry's law, which takes the form:

$$p_A = H\, x_A \tag{10.4}$$

where H is Henry's constant, corresponding to temperature T.

If the partial pressure is expressed by equation (10.3), the concentration of the dissolved component A in the liquid which is in equilibrium with the gas in which component A has the concentration y_A is calculated from equation (10.4)

$$x_A = \frac{p}{H}\, y_A \tag{10.5}$$

The values of Henry's constant are stated, for example, in the Perry and Green handbook for various gases and temperatures.

Absorption can be:

- ***physical*** – one component of the gas has greater solubility than the others,
- ***chemical*** – is based on the reaction of the component which is to be separated by the solvent.

APPARATUSES

Equipment for the contact of gases and vapours can, according to construction arrangement, be divided into:

- ***tray columns,***
- ***packed columns,***
- ***mechanically mixed tanks,***
- ***static mixers.***

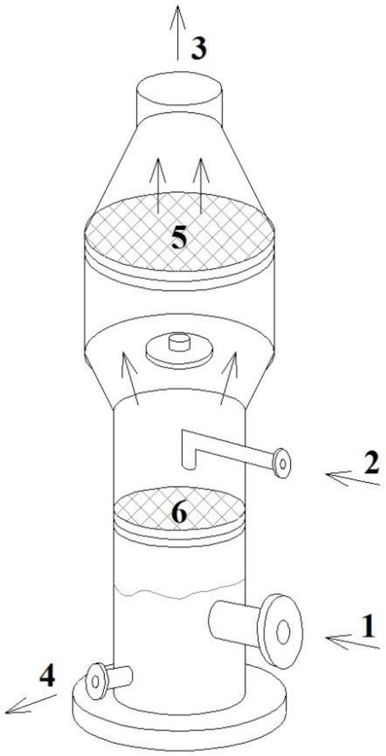


Fig. 10.2. Column apparatus for absorption (absorber) [6]:
1 – gas entry, 2 – liquid entry, 3 – gas exit, 4 – liquid exit,
5 – demister (droplet separator), 6 – separation screen

Absorption is often used as a separation process in the chemical technology for separating certain components of a gas mixture by their absorption in liquid. It is usually followed by desorption. This is the opposite process, in which the absorbed component is separated from the solvent. Its goal is to separate the absorbed component from the solvent in order to gain a pure absorbed component or regeneration of the solvent.

In designing an absorber, it is necessary to execute the following steps and calculations:

- *number of contact degrees (e.g. trays),*
- *hydrodynamic calculations (pressure losses, permitted speed, overloading of the column, gas trap, power input for mixing),*
- *heat calculations (heat profiles, heat losses),*
- *material transfer (transmission and mass transfer coefficients, efficiency),*
- *selection of operating parameters (retention time, volumes, diameters, temperatures, pressures)*
- *stability calculations (wall thickness, flanges, column stability).*

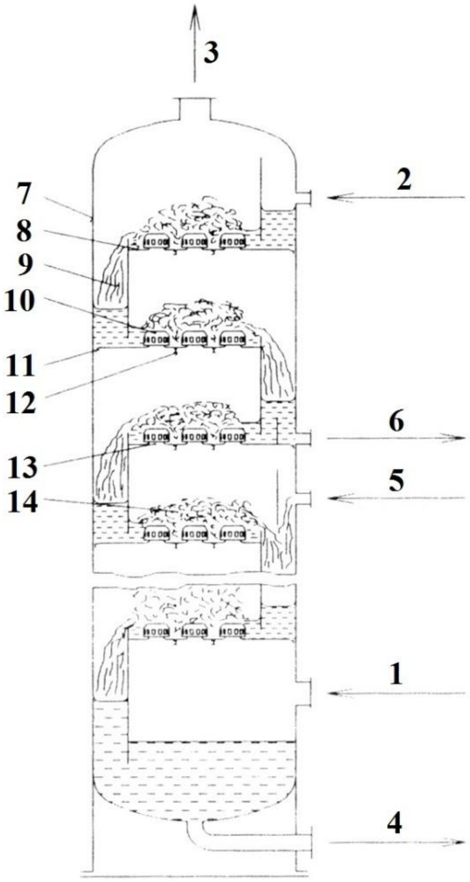


Fig. 10.3. Column tray apparatus for absorption [6]:
1 – gas entry, 2 – liquid entry, 3 – gas exit, 4 – liquid exit,
5 – side liquid entry, 6 – side liquid exit, 7 – column apparatus cover,
8 – tray, 9 – fall of liquid, 10 – bubble-cap, 11 – ring support, 12 – tray support,
13 – bubble-cap neck, 14 – foam

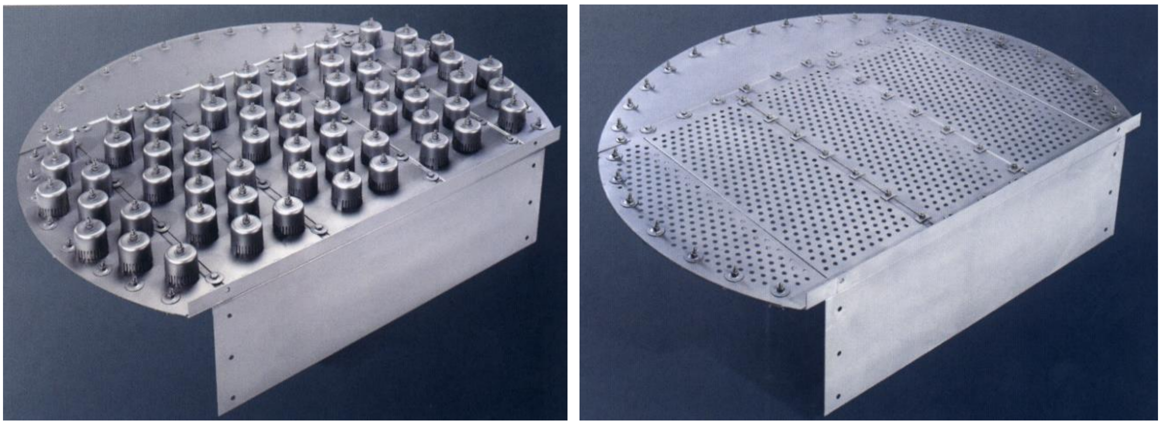


Fig. 10.4. Trays of column apparatus for absorption [9]

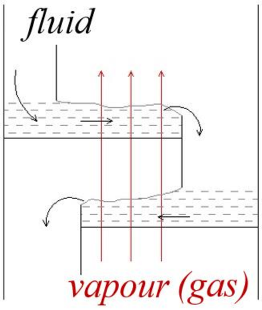


Fig. 10.5. Gas and liquid flow direction on tray in column apparatus [6]

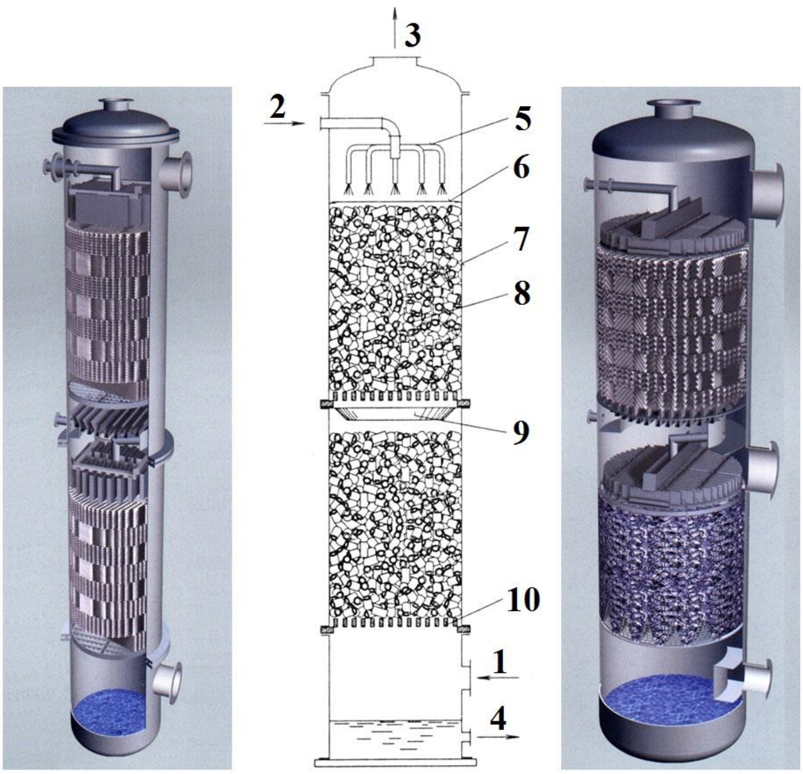


Fig. 10.6. Different types of filler columns [6, 9]
1 – gas input, 2 – liquid input, 3 – gas exit, 4 –liquid exit,
5 – liquid distributor, 6 – distance sieve, 7 – column apparatus cover,
8 – filler, 9 – liquid redistributor, 10 – bearing grill

Fig. 10.7. Liquid distributor in column apparatus [9]

LIST OF SYMBOLS

p	–	pressure	(Pa)
p_i	–	partial pressure of i^{th} component	(Pa)
x	–	mole fraction in liquid state	(1)
x_i	–	mole fraction of i^{th} component in liquid state	(1)
y	–	mole fraction in gas state	(1)
y_i	–	mole fraction of i^{th} component in gas state	(1)
H	–	Henry's constant	(Pa)
K	–	distribution coefficient	(1)
T	–	temperature	(K)

11 EXTRACTION

In fluid extraction, one or more fluid components are removed from the solution by means of a second fluid phase that is not mixable or only slightly mixable with the original solution.
The principle of extraction works with a fluid mixture from which it is necessary to separate a certain component brought into contact with another fluid – solvent (extractant) – in which the separated component dissolves better than the rest of the components of the mixture. The condition for the successful separation of the extracted component is insolubility or as little solubility as possible in the new solvent (extractant).

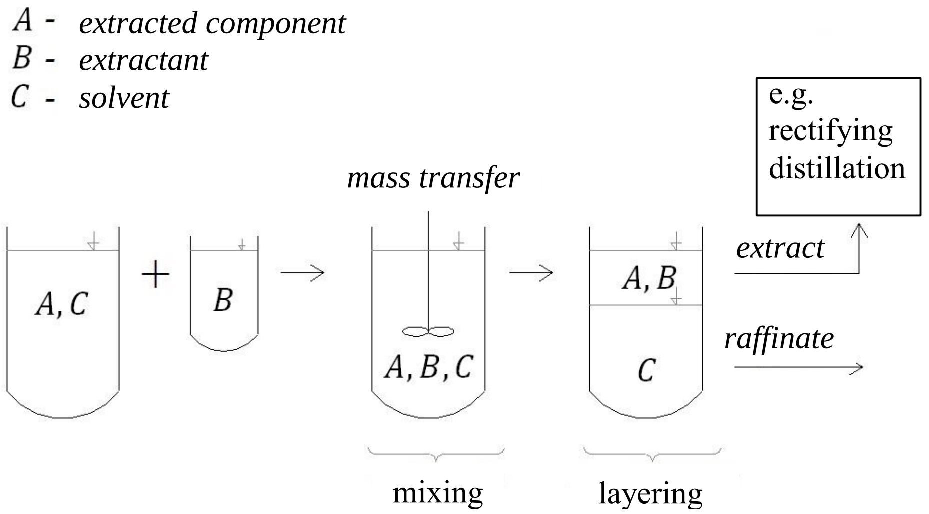


Fig. 11.1. Principle of extraction in a fluid [6]

The components of solutions A and C are mutually soluble. Component A is the extracted component and component C is the solvent. Components A and C cannot be separated by distillation for some of the following reasons:

- the boiling points of components A and C are too close,
- the materials form an azeotrope.

The principle of extraction is then the following: To a mixture of material A and C is added material B – a so-called extractant, to which material A binds. The extractant must have the following properties:

- the extractant and the solvent must be mutually unmixable or mixable to only a small degree,
- the phase equilibrium, i.e. the separation of component A between solvent C and extractant B, must be favourable for B.

With the addition of the undissolved extractant, it is necessary to disperse it by thorough mixing i.e. form a great amount of small droplets of the dispersed phase, by which we get a large inter-phase surface and so allow the rapid transport of material A to the extractant.
To reach equilibrium, or at least to approach it, it is necessary to separate the undissolved phase. For this their different densities are generally used, so that the phases are easily separated by gravity. The phase formed mostly by the extractant is called the extract and the phase formed mostly by the solvent is called the raffinate. The extract, the mixture of the dissolved materials A and B, is easily separated by, for example, distillation.

Equilibrium requires mutual solubility of the components involved: A – extracted material, B – extractant, C – solvent.

A theoretic description of the equilibrium by means of the active coefficients is so complex that in technical practice it is based exclusively on experimental data. These may be presented:

- by different methods of graphic expression that may be depicted in a triangular diagram or in a so-called distribution diagram,
- by empiric correlations of the equilibrium data.

APPARATUSES

MIXER – SEPARATING TANK

This construction combines two pieces of equipment in one. In the mixer the dispersing phase takes place, while in the separating tank the extract and the raffinate are separated by gravity as a result of their differing densities. The important factor is the dimensions of the droplets, which must be a compromise between the requirements for mass transfer (droplets as small as possible) and a suitable sedimentation time (proportionate droplet size). Under advantageous conditions, 99 % separation of the extract and the raffinate can be achieved, with up to 90 % step efficiency.

Advantages:

- independent choice of the dispersing grade because the mixer is not influenced by the hydrodynamics of the other part,
- a wide range of equipment performance, while retaining efficiency,
- the equipment is ergonomic,
- suitable for extreme phase relations,
- easy to continue to the next step.

Disadvantages:

- large working area,
- a great amount of equipment, thus affecting the cost of the required extractant.

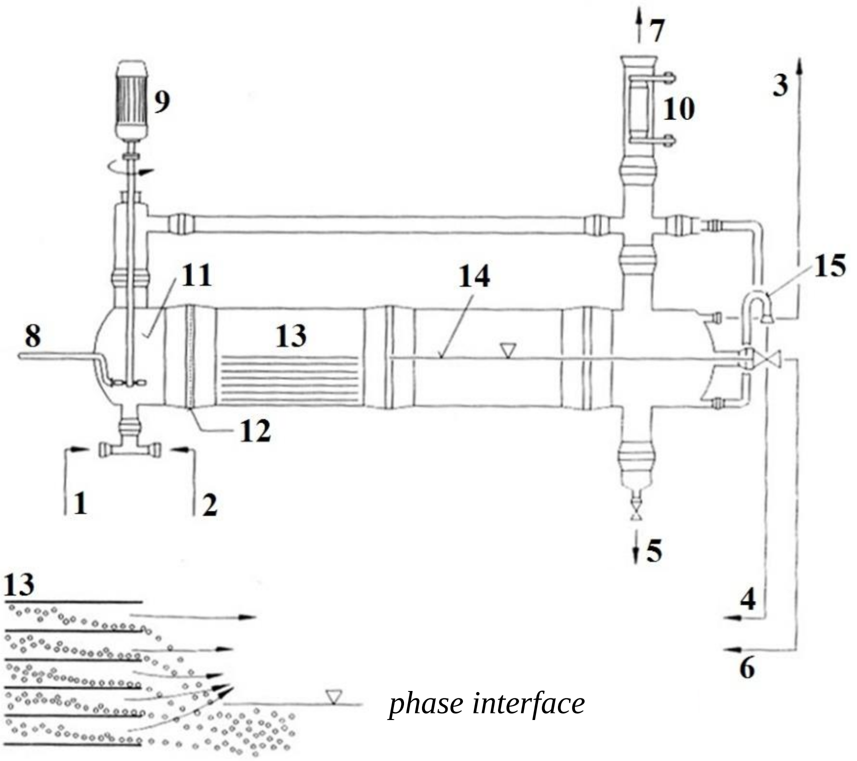
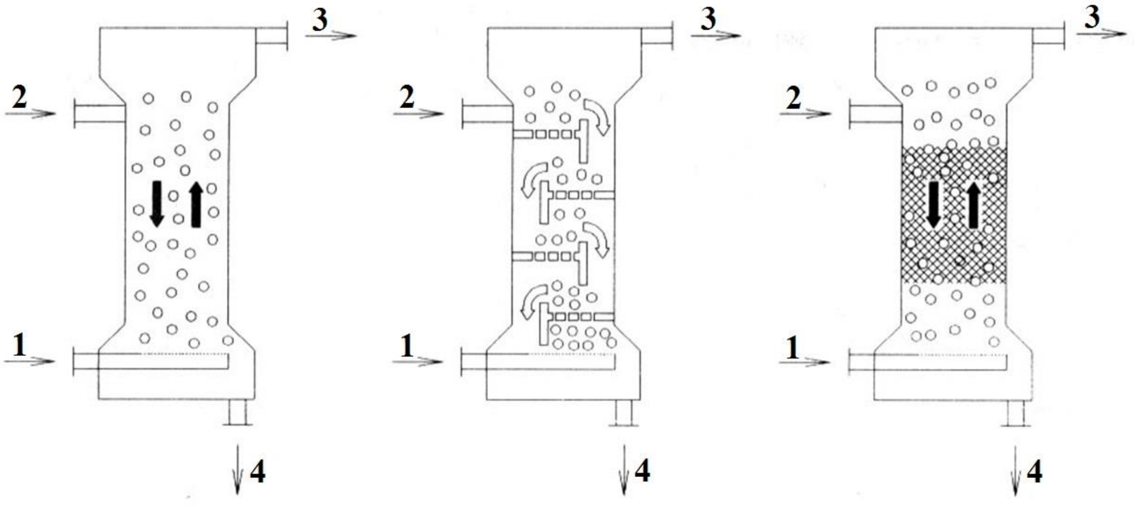


Fig. 11.2. Diagram of a compact mixer-separator extractor [6]:
1 – input of light phase (e.g. extractant or extract),
2 – input of heavy phase (e.g. extracted component and solvent or raffinate),
3 – output of light phase, 4 – output of heavy phase, 5 – decanting,
6 –sludge output from phase interface, 7 – degassing, 8 – thermometer, 9 – motor,
10 – gas cooler, 11 – mixing chamber, 12 – screen, 13 – sedimentation lamellas,
14 – phase interface, 15 – setting of extent of phase interface



a *b* *c*

Fig. 11.3. Main types of feeder columns [6]:
a – sprayer column, b – column with screen trays, c – feeder column,
1 – input of light phase, 2 – input of heavy phase, 3 – output of light phase,
4 – output of heavy phase

This process is often used in petro-chemistry or for the separation of aromatic hydrocarbons (benzene, toluene, xylene) from paraffin. In the pharmaceutical industry, penicillin is obtained in this way from a centrifuged fermenter batch. Included among extraction processes there is also maceration, which is the extraction of one or several components, of the solid phase by fluid. It is used for example for obtaining healing materials from plants (tea, coffee and the like.)

12 ADSORPTION

Absorption is the process in which the retention of a substance in the solid material phase interface takes place. The substances may be either gas or fluids. An absorbent is a solid material on the surface of which adsorption occurs. An adsorbate is a component of a solution which is transferred to an adsorbed state. Desorption is the transferring of the adsorbate from the surface of the adsorbent back to the solution.

The physical property of solid materials- the ability to concentrate on the surface of a gas, vapours and liquid is used.
The principle of adsorption consists in the fact that on the surface of an adsorbent of several hundreds of $\mathrm{m}^2.\mathrm{g}^{-1}$, the molecules or ions of the adsorbate are physically or chemically bound. Their amount is given by the adsorption equilibrium.

From the point of view of binding forces, several types of adsorption exist.

- ***Physical adsorption***
  This is caused by the Van der Waals forces of attraction. These forces bring about the capture of the molecules of the adsorbed material in the adsorbent at a temperature higher than the condensation temperature of the pure material. In the first phase, the surface is covered with molecules in one layer (mononuclear layer), on which other layers of molecules are subsequently captured, with the thickness of the layer given as a consequence of the Van der Waals forces. The speed of such adsorption is significant and may easily desorb the adsorbed material. This is a reversible process. Pure physical adsorption is an exothermic phenomenon, during which there occurs an adsorption temperature which is about 15 to 20 times higher than the condensation heat. Adsorption caused by the Van der Waal forces is not particularly selective: i.e. the individual properties of the adsorbed materials do not have a significant influence on their capture on the surface of the adsorbent.
- ***Chemical adsorption***
  - *Activated adsorption* is caused by inter-molecular chemical bonds without leading to the formation of a new compound. The reverse process is relatively difficult. It is an exothermic phenomenon during which heat close to the values of the reaction heat is released.
  - *Chemisorption* on the surface of a firm material binds molecules from the environment, with the resultant formation of a new chemical compound. The speed of this reaction is significantly greater than the previous one, and is dictated by the reaction speed. It is an irreversible exothermic event during which the released heat is equal to the reaction heat. It is a selective process.

ADSORBENTS

These are porous materials with a large surface area. Usually they are granulated into balls or pressed into tablets. Among the most used are:

- ***activated carbon***
  Results from the carbonization of coal, wood or coke. Activation (partial oxidation process) is performed by hot air or steam. It is used for the adsorption of organic solvents, the filtration of beer, wine, oil and similar.
- ***silicates* - $\mathbf{SiO_2}$**
  Used for the drying of air and gases.

- ***alumina*** **- Al_2O_3**
  It is used as a catalyst carrier and is activated by heating.
- ***adsorption clays***
  Among these are bauxite, bentonite and kaolin. Activated by heat.
- ***• bone meal***
  Used for sugar purification.

The complexity and variety of the forces applied during adsorption and the possibility of their mutual combination are the reasons why in this area it has so far been impossible to make many generalizations that could be used for calculations. In spite of this, many works dealing with the formulation of equilibrium dependencies have been undertaken.

The principle of calculation starts with an equilibrium curve referred to as the adsorption isotherm. It describes the equilibrium achieved between the adsorbate on the surface of an adsorbent and a fluid or gas solution. At a given temperature and solution concentration, the adsorbent accepts only a certain amount of material A, designated q_A (kg *A*/kg *of adsorbent*).

Therefore, for gases there applies:

$$q_i = f(T, p_A, p_B, p_C, \dots, history) \tag{12.1}$$

For fluids there applies:

$$q_i = f(T, c_A, c_B, c_C, \dots, history) \tag{12.2}$$

“History” means the path of adsorption / desorption loops in completed cycles. For gases it can have a substantial effect, but for liquids it is negligible.

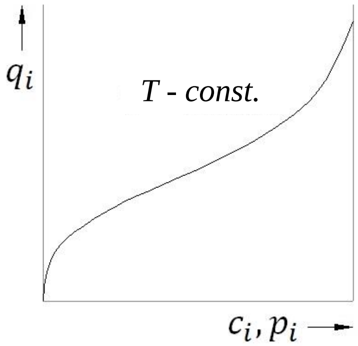


Fig. 12.1. Adsorption isotherm[6]

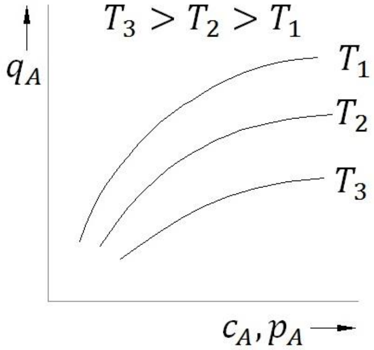


Fig. 12.2. Effect of heat [6]

APPARATUSES

In figure 12.3 is depicted an absorber in which the gas or fluid passes through the static layer of an adsorbent that is spread on grills.

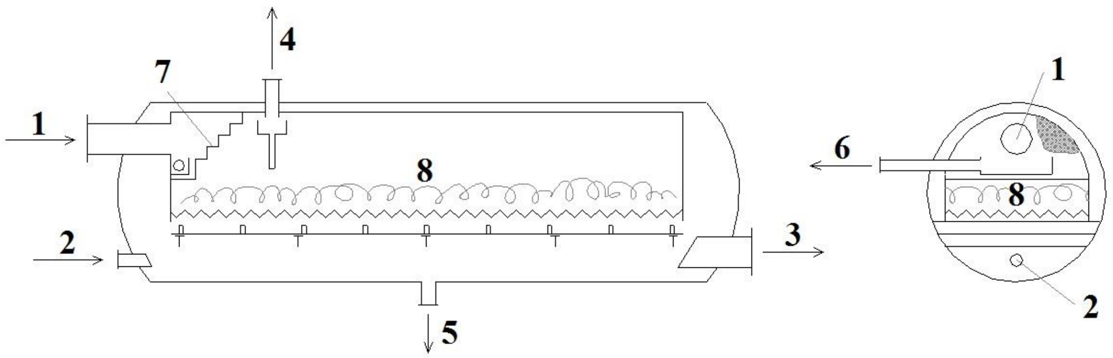


Fig. 12.3. Horizontal adsorber with stationary layer of adsorbent [6]:
1 – input of steam-gas mixture, 2 – input of steam, 3 – output of gas,
4 – output of water steam and desorbed vapours, 5 – output of condensate,
6 – output of captured drops, 7 – sieve, 8 – adsorption bed

The steam-gas mixture, from which steam is to be separated and pure gas obtained, enters the vessel. This mixture runs through a screen sieve and the adsorption layer where, in this case, the steam element is captured. Pure gas is on output. The adsorption layer is regenerated due to the steam which enters below the grills, runs through them, and takes with it the desorbed vapours. The part of the steam which is condensed is run though the condensate output pipe.

Adsorption is a non-stationary process because the layer of adsorbent on the grills is progressively filled with the adsorbed material. It is necessary to regenerate the adsorbent after its filling by increasing the temperature, reducing the pressure, or with an inert gas. All of these methods release the adsorbed material and regenerate the adsorbent.

In industrial applications, adsorption is most frequently used for:

- ***cleaning of gases*** (drying of gas, removal of CO_2, SO_2, separation of hydrocarbons – methane, ethylene, ethane, propylene, propane, production of oxygen and nitrogen)***,***
- ***cleaning of fluids*** (decolourisation of oil products and sugar...)***,***
- ***gaining of valuable raw materials from diluted solutions,***
- ***separation of gases and fluids,***
- ***chromatographic analytics.***

LIST OF SYMBOLS

c_i – mole-volume concentration of component i $(\mathrm{mol.\,m^{-3}})$
i – component (1)
p_i – partial pressure of component i (Pa)
q_i – mass fraction (1)
T – temperature (K)

13 BIOPROCESSES

Bioprocesses can be understood as specific processes by which desired products are obtained with the use of living cells or their parts. The UN Agreement on Biological Diversity defines biotechnology as the usage of living systems and organisms for the creation of products or any kind of technology that employs biological systems, living organisms or their derivatives for the production or modification of products or processes.

BASIC CONCEPTS FROM THE FIELD OF BIOCHEMISTRY

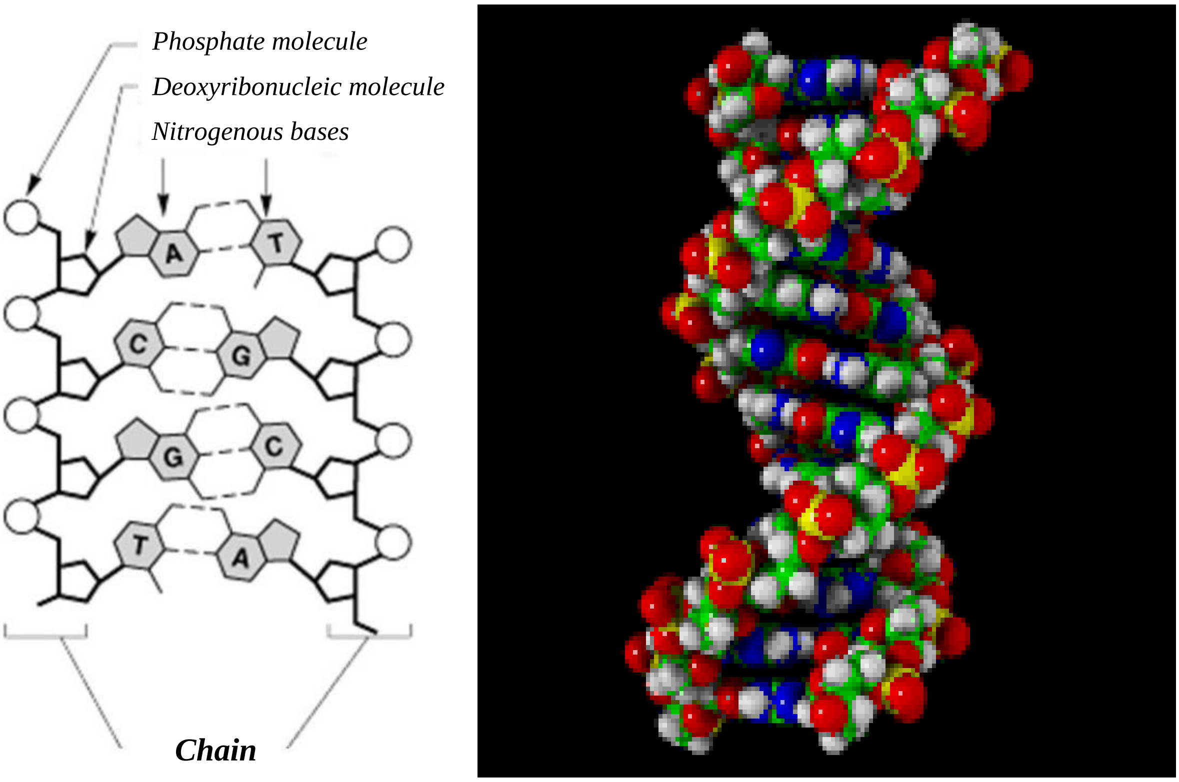
Their common trait is the fact that they define the state and structure of microorganisms and their resultingspecific properties, which are used in bioprocesses to obtain products with the desired characteristics.

- ***BASE***
  is a chemical compound made up of the elements carbon C, nitrogen N, hydrogen H and oxygen O. According to the way in which the molecules are arranged, they create compounds named cytosine, guanine, adenine, thymine and uracil. They form complementary pairs. Guanine bonds with cytosine, and adenine with thymine. They form codes for the writing of genetic information. Complementary pairing then permits this information to be taken advantage of in the processes of replication, transcription and translation.

- ***DNA***
  is the designation for deoxyribonucleic acid, therefore the polymer made up of deoxyribonucleotides. Along with ribonucleic acid (RNA), it belongs among so-called nucleic acids because they were discovered in the cell nucleus. DNA is the carrier of the cell’s genetic information, and manages growth, division and regeneration. In general, DNA is stored in the cell as a twin-screw spiral whose filaments have opposing orientations of phosphodiester bonds (they are anti-parallel). The basic components of DNA, its monomers, are called deoxyribonucleotides or generally nucleotides. Each nucleotide is made up of three elements:
  - phosphoric acid phosphate residue ($(PO_4)^{3-}$),
  - deoxyribose molecules,
  - nitrogen base.

  There are four nitrogen bases forming the structure: adenine (A), guanine (G), cytosine (C) and thymine (T). They bind the two threads of double-threaded DNA using hydrogen bonds, and the principle of complementariness of bases still applies. Complementariness means that in DNA, adenine prefers to bond with thymine from the second twin thread, and guanine with cytosine.

  The order of the individual nitrogen bases is key in gene transfer information. Functional DNA segments that can translate certain enzymes into RNA are called genes. RNA originates by transcription from DNA, while thymine from DNA transcribes to uracil.



a *b*

Fig. 13.1. Four nitrogenous DNA bases are arranged along the sugar-phosphate chain in individual sequences (DNA sequences), thus codifying genetic information for the organism. Adenine (A) bonds with thymine (T) and cytosine (C) bonds with guanine (G). Two twisted DNA strands are linked by weak bonds between the bases [42]:
a – schematic illustration of DNA, b – spatial model of DNA helix

- ***RNA***

  is the designation for ribonucleic acid. It is a nucleic acid composed of one strand of covalently bound ribonucleotides. One of the main functions of RNA is the copying of genetic information from DNA (transcription) and physically transferring it to the place where its transfer (translation) occurs to the resultant protein (only one class of RNA directly fulfills this function, mediator RNA (mRNA).

  RNA is composed of four different bases: adenine, guanine, cytosine, and uracil. The first three are identical with those found in DNA, but the uracil in RNA replaces thymine in its complementary function to adenine.

- ***GENE***

  is a DNA or RNA sequence which codifies information for the creation of a given product. In a narrow sense, a gene codifies the creation of one protein. There exist a number of different definitions for a gene, often adapted to the needs of individual scientific disciplines. The gene is the basic functional unit for inheritance.

  The gene codifying protein is composed of triplets - codons- each triplet presenting information about the arrangement of one amino acid. At the same time, a gene must also contain a sequence allowing its regulation. Here feature sequences designating the place of the beginning and the end of the gene transcription. These codons do not codify amino acids, but provide the information without which the successful course of proteosynthesis would not be possible. Codon fragments without functional regulatory sequences are called pseudogenes.

• ***GENOME***
is the complete genetic information stored in the DNA of a specific organism. It includes all genes and non-coding sequences.

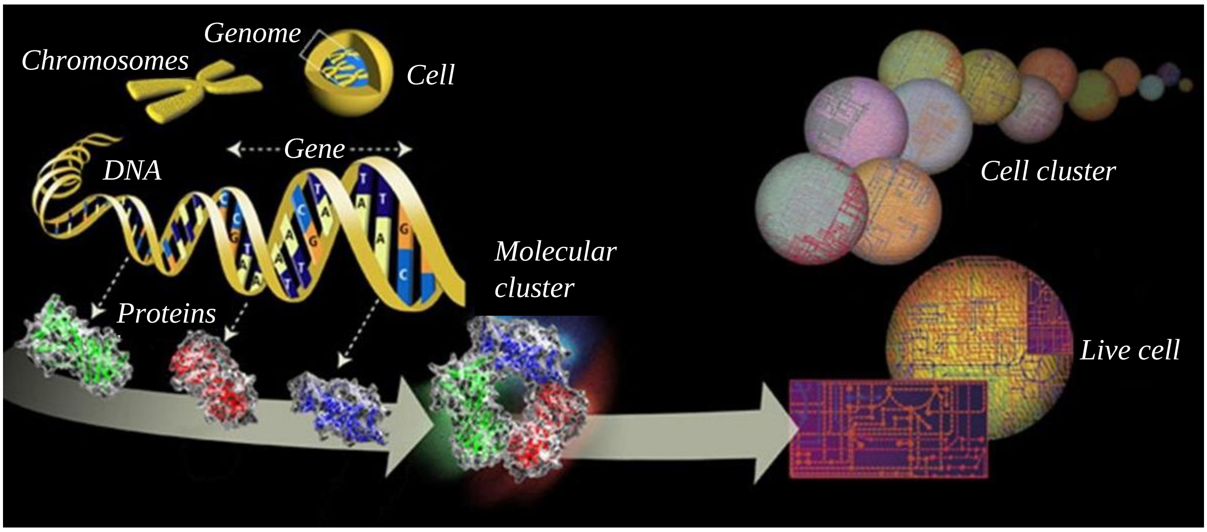


Fig. 13.2. Constructional elements in live organisms [42]

MICROORGANISMS USED IN BIOPROCESSES

A microorganism is a microscopic live organism that is made up of one cell or a number of cells. According to the number of cells, an organism is single-cell or multi-cell.

Microorganisms are very varied, and in this category are classified:

- ***Viruses***
  The only organisms that do not have a classic cell structure. Neither do they have the ability to reproduce independently, and reproductions are possible only in a live cell. An example of the use of viruses in technology is genetic engineering, where they are used as carriers of genetic information [11].

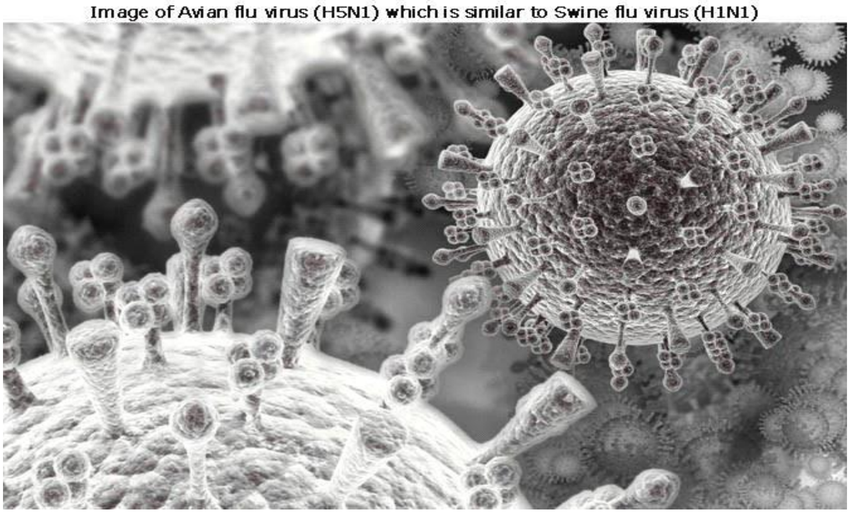


Fig. 13.3. Flu virus H5N1[45]

- ***Bacteria***
  are single-cell organisms whose body is formed of one prokaryotic cell. The cell structure of bacteria is simpler than for other organisms. They do not have an independent nucleus; the genetic information is contained in one DNA loop. Some bacteria have an additional circle of genetic material called a plasmid. True plasmids often contain genes that give these bacteria a certain advantage over other bacteria. For example, a plasmid may contain a gene which makes the bacteria resistant to a certain type of antibiotic. Basic bacterial functions include nutrition and reproduction.

  The basic differences in bacteria according to shape are:
  - coccus – ball-shaped bacteria,
  - bacillus – rod-shaped bacteria,
  - spiral – spiral-shaped bacteria,
  - spirochete – long, thin, helically curved bacteria,
  - vibrion –curved rod shaped bacteria.

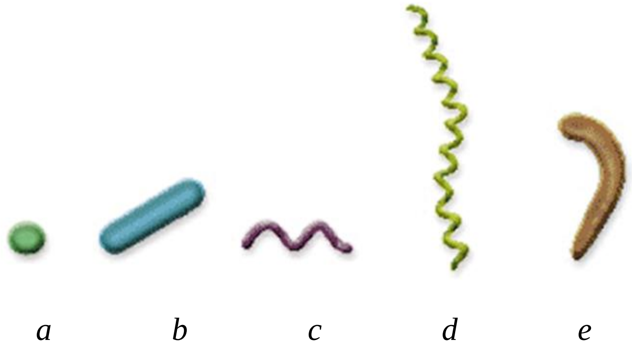


Fig. 13.4. Basic bacteria shapes [46]:
a – coccus, b – bacillus, c – spiral, d – spirochete, e – vibrion

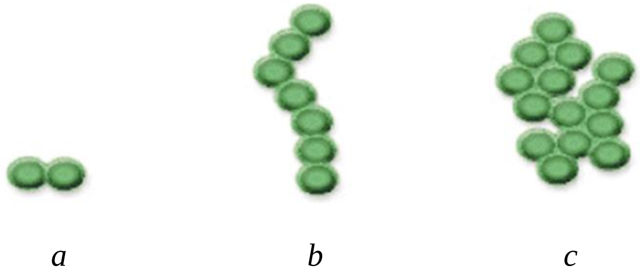


Fig. 13.5. Examples of arrangement of coccus bacteria in colonies [46]:
a – diplococci, b – streptococci, c – sarcina

The usage of bacteria is quite widespread in the biotechnological industry. Bacteria may be used in the biodegradation of organic materials or for mineralization, cleaning of water, soil or sediments. They are also used for breaking down organic materials and reducing odours (e.g. active sludge). Bacteria are also used in genetic engineering. [11].

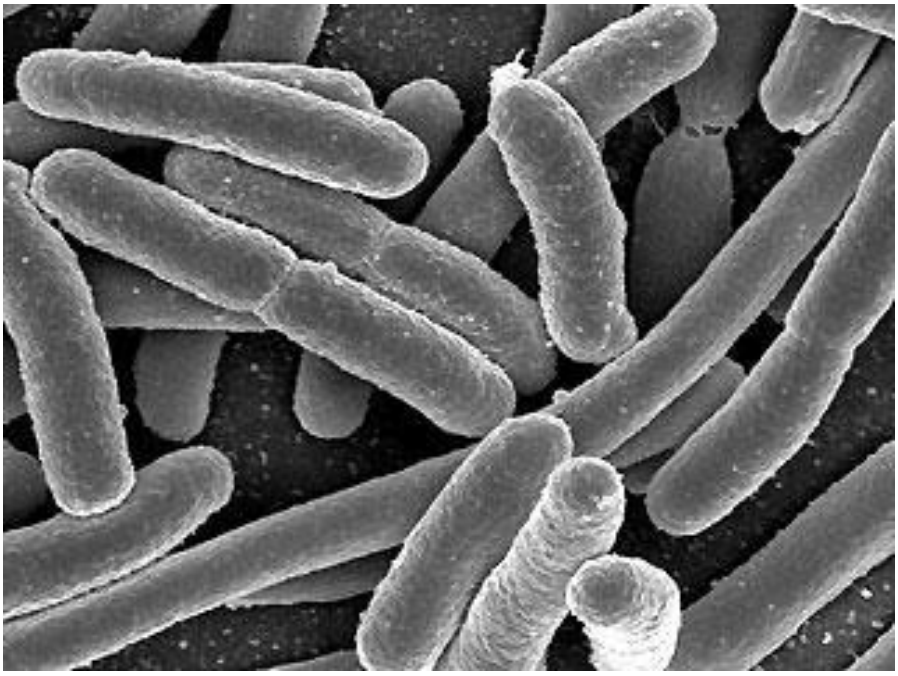


Fig. 13.6. Escherichia coli bacteria [41]

- ***Yeasts***
  are single-cell organisms that belong to the ascomycota or basidiomycota fungi classes. They mostly reproduce by cross-sectional division. Yeasts are rich in sugars, well-digestible proteins and vitamin B (mainly brewer's yeasts). Yeasts are used in the production of alcohol (wine, beer, spirits), as well as in baker's yeast and some types of milk drinks [11].

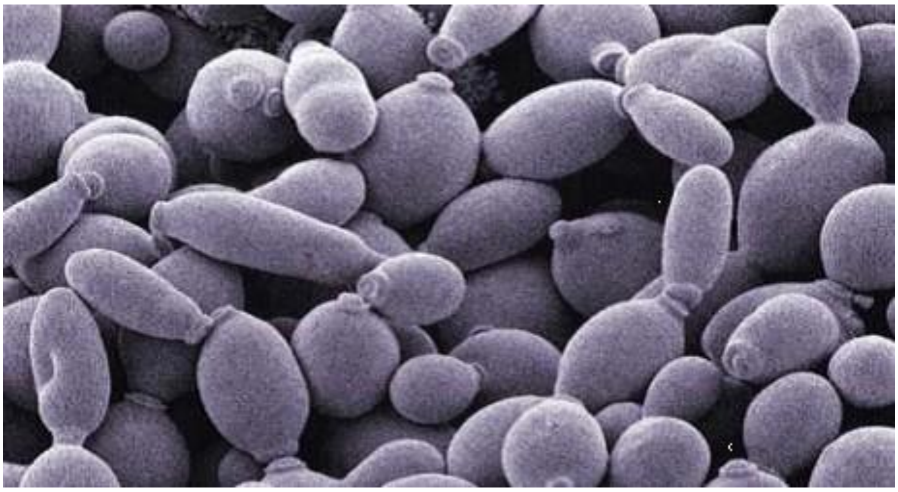


Fig. 13.7. Saccharomyces cerevisiae yeast [49]

- ***Algae***
  are photosynthetic water organisms that contain chlorophyll. Their bodies are made up of eukaryotic cells. In biotechnological processes, algae can be used in the food (source of proteins) and pharmaceutical (antibiotics) industries, or in the production of agar [11].

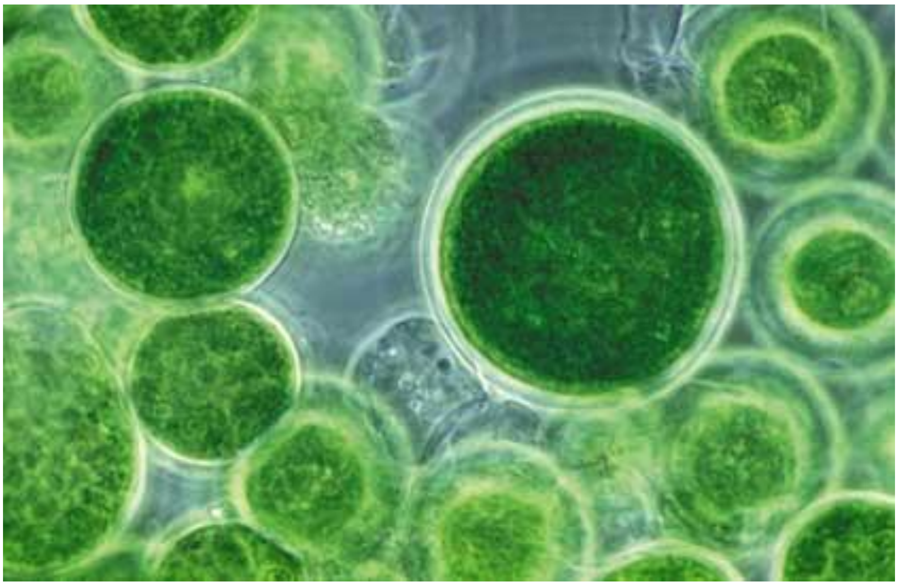


Fig. 13.8. Saccharomyces cerevisiae algae [50]

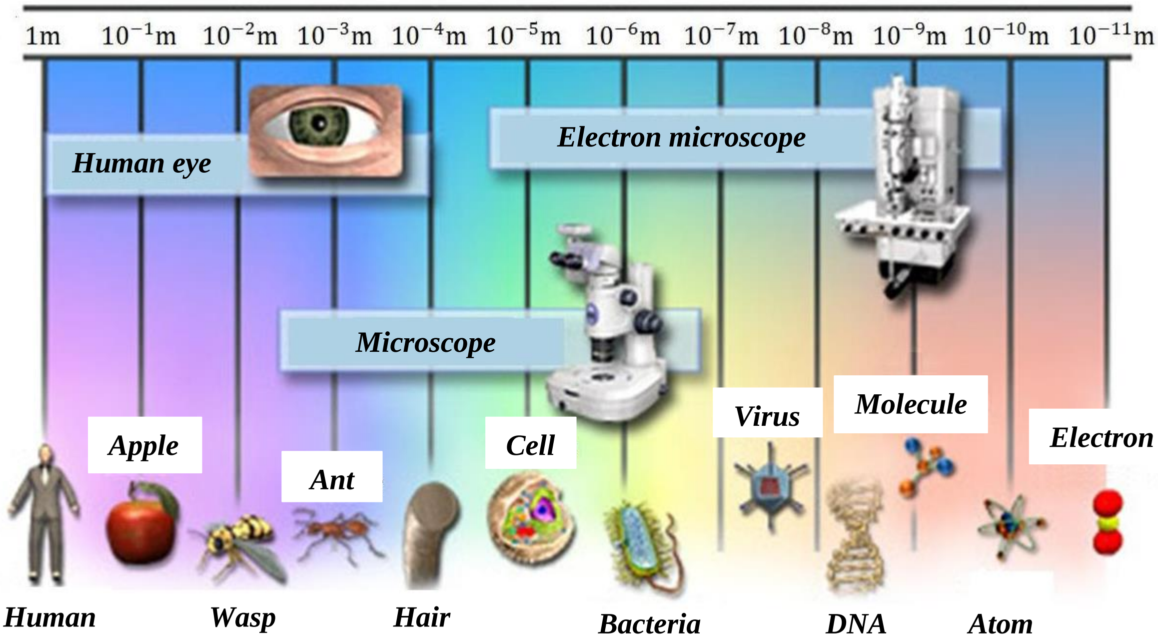


Fig. 13.9. Particle size [40]

PRINCIPLE OF FERMENTATION PROCESS

The process of fermentation is a specific biochemical process which from the biochemical standpoint is a set of chemical changes produced in compounds (substrates) by the activity of living microorganisms. In these processes, the microorganisms are used for the change of one substance into another.

The concept of fermentation was originally associated with bubbling or boiling, and was used to describe the fermentation process in making wine. Only later did it begin to be associated with microorganisms and enzymes. Accordingly, this term can be defined as the process during which chemical changes in an organic substrate are brought about by the effect of enzymes.

Fermentation describes enzymatic, dissimilatic, partial transformations of organic substances, especially carbohydrates, into simpler substances with the accompanying release of energy. Originally only anaerobic processes (true fermentation), were classified among them, but later aerobic processes (false fermentation) were included. These processes are either homo-fermentation (when only one product is formed) or hetero-fermentation (several products are formed). Fermentation may bring about cells of all kinds of organisms. Microbic fermentations have technical applications. The process of fermentation has been used for hundreds of years in the production of various foodstuffs. Such uses include bread, beer, buttermilk, sterilized vegetables, yogourt and others.
Before the work of Louis Pasteur, there was little information about the process of fermentation or the effect of microorganisms. Louis Pasteur's discoveries led to the development of large production bioreactors for bacteria and yeasts.

In general, fermentation causes the breakdown of complexes of organic substances into simpler forms. Small cultures were first created in dishes which could not however create a sufficient amount of products of fermentation (acetone, ethyl alcohol...). These products were of great value, since they could not be produced in great volumes. In order to increase the production of biocultures, bioreactors were developed at the beginning of the 20th century. These allowed the production of larger volumes of these products, up to several thousand litres.

Fig. 13.10. Small cultures were originally created in dishes [42]

For the most part, the process takes place at normal temperatures and pressures. A low value of concentrations is favourable for microbiologic processes. The substrate concentration is from 12 – 15 %, concentration of cells 2 – 4 %. The majority of fermentations have an aerobic nature, i.e. the microorganisms for their metabolisms need oxygen in addition to nutrients (substrate). The provision of oxygen occurs through the rising of air bubbleswhich diffuse into the liquid phase containing microorganisms. The oxygen too must go through a series of resistances whose size depends on the hydrodynamics of the bubbles, on temperature, microbial activity and density, the composition of the solution, interphasal factors, and other agents. So it depends on the combination of resistances, as can be seen below:

- diffusion from the main flow of gas on the gas – fluid interface (layer δ_G),
- movement through the gas – fluid interface (partial coefficient of the transfer of oxygen in the gas-side diffusion film layer at the gas – fluid interphasal interface),
- diffusion through the boundary layer to the main fluid flow (layer δ_{L1}),
- transport from the main fluid flow into the boundary layer on the surface of the microbial particles,
- diffusion through this boundary layer to the surface of the microbial particles (layer δ_{L2}),
- diffusion in microbial flakes or film onto the individual cells of the surfaces of the microorganism,
- consumption of oxygen in the cells of the microorganism by biochemical reaction.

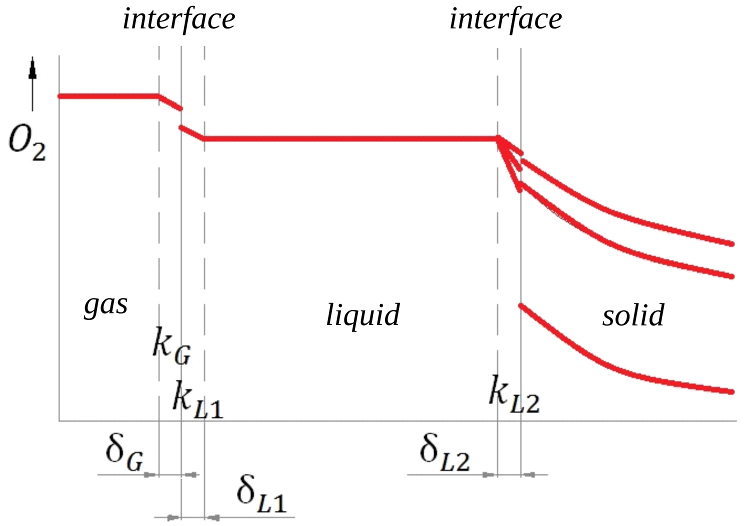


Fig. 13.11. Illustration of resistances against oxygen transfer [18]

If microorganisms adsorb on the bubble-fluid interface, the oxygen travels through only one unmixed fluid interface and does not pass through the main fluid volume (Fig. 13.12b).
The solubility of oxygen in water under pressure is shown in Table 13.1. It is of relatively small content because the consumption of oxygen, in accordance with the type of process, is for example 6 $\mathrm{g.l^{-1}.h^{-1}}$. This is why oxygen must continually be added to the culture, because otherwise it would die.

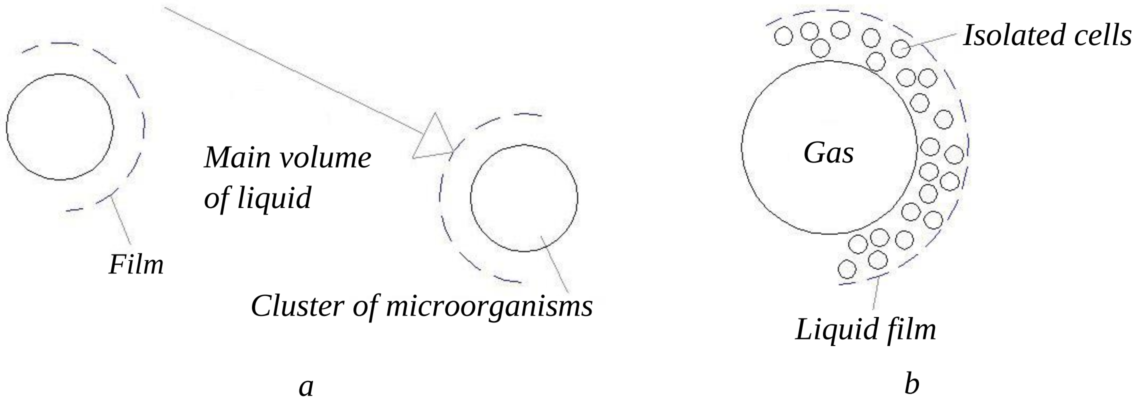


Fig. 13.12. Schematic representation of the transfer of oxygen to the surface of microorganisms [18]:
a – separate bubble and cluster of microorganisms, b – bubble-based microbes

Table 13.1. Solubility of oxygen in water under pressure

Temperature	Concentration in water	Temperature	Concentration in water
0	14.65	25	8.18
10	11.27	30	7.44
15	10.03	35	6.99
20	9.02		

In the production of the desired products in bioreactors, various parameters play a role. These include:

- substrate,
- substrate consumption,
- requirements for nitrogen,
- supplying amino acids,
- oxygen concentration,
- temperature,
- pH,
- pressure.

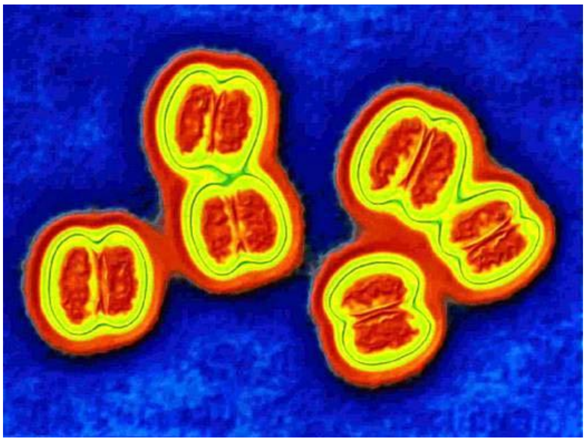


Fig. 13.13. Growth of cultures by division [42]

METABOLISM

Enzymes are specific proteins that function as biocatalyzers. They may appear directly in the cell (in vivo) or outside of it (in vitro).

With the help of enzymes, organisms perform certain chemical processes that are collectively labelled metabolism (metabolic processes). The metabolic processes of organisms are similar because all organisms must synthesize universal compounds of a living material from external building units. Similarly, they must release the energy for these processes of synthesis of the new cell material.

The majority of microorganisms are very active in the performing of chemical changes. An indication of this activity is the time necessary for the given biological cluster to double its weight. It is also assumed that the growth process is not limited by the supply of nutrient materials. For example, this is from 0,3 – 2 hours for bacteria, moulds and yeasts.
Microorganisms need energy, oxygen, hydrogen and mineral materials for their nourishment.

The source of energy and carbon is an organic compound that is oxidized while at the same time releasing energy providing carbon for the synthesis of new cell materials. Total metabolism is exothermic. The energy released by oxidizing reactions is partially absorbed in synthetic reactions, while the rest is gradually released into the surrounding environment as heat.

GROWTH PHASES

The growth of bacteria cultures can be represented by a curve which is made up of four phases:

- *delay phase* – growth and reproduction are just starting,
- *exponential phase* – reproduction takes place in exponential growth,
- *stationary phase* – the environment surrounding and supplying nutrients can no longer support exponential growth,
- *declining phase*– population dies off when all nutrients are consumed.

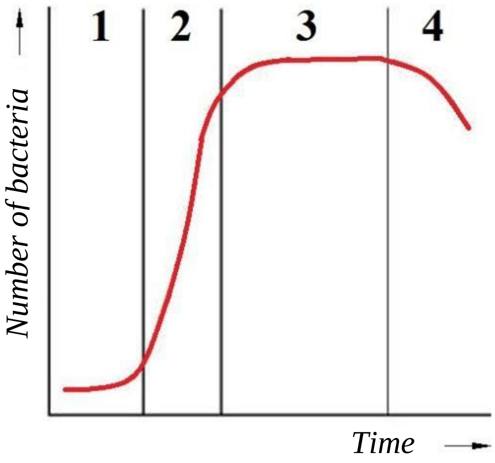


Fig. 13.14. Bacteria growth curve [18]:
1 – delay phase, 2 – exponential phase, 3 – stationary phase, 4 – declining phase

The production of metabolites (such as antibiotics) often occurs during the stationary phase.

CELL CULTURES

- cell cultures are obtained by special techniques.
- microorganism cultures are obtained by:
  - isolation from natural sources (vinegar bacteria, wine yeasts),
  - selection, by enriching, by mutations,
  - gene manipulation.

MEDIA (CULTIVATION AND PRODUCTION)

Most bacteria are heterotrophic. As a source of energy, they require some organic material which is also the main source of carbon for the synthesis of compounds of biomass and final products. The most universal are sugars, particularly glucose. Under optimal conditions, aerobic microorganisms change about 60 % of carbon from the biomass, while the rest is in the form of CO_2. The media also contain oxygen (in aerobic processes), the hydrogen contained in water, and nitrogen, which is supplied in the form of ammonia or ammonium salts, for example. Apart from this, phosphorus, potassium, sulphur, iron and the like are added to the cultivation media as trace elements supporting the growth of microorganisms.

PROPAGATION (MULTIPLICATION) OF INOCULUM

An inoculum is a batch of microorganisms in a given environment, such as a cultivation or production medium. Propagation of an inoculum is an almost indispensable intermediate step between the laboratory and the operating conditions of bioreactors, keeping cultures alive in the production bioreactor. Ordinarily a 10 % volume of inocula is used. For example, in the production of beer an inoculum made up of beer yeasts which are in 8 – 10 % aqueous sugar solutions is used. This environment allows them to multiply.

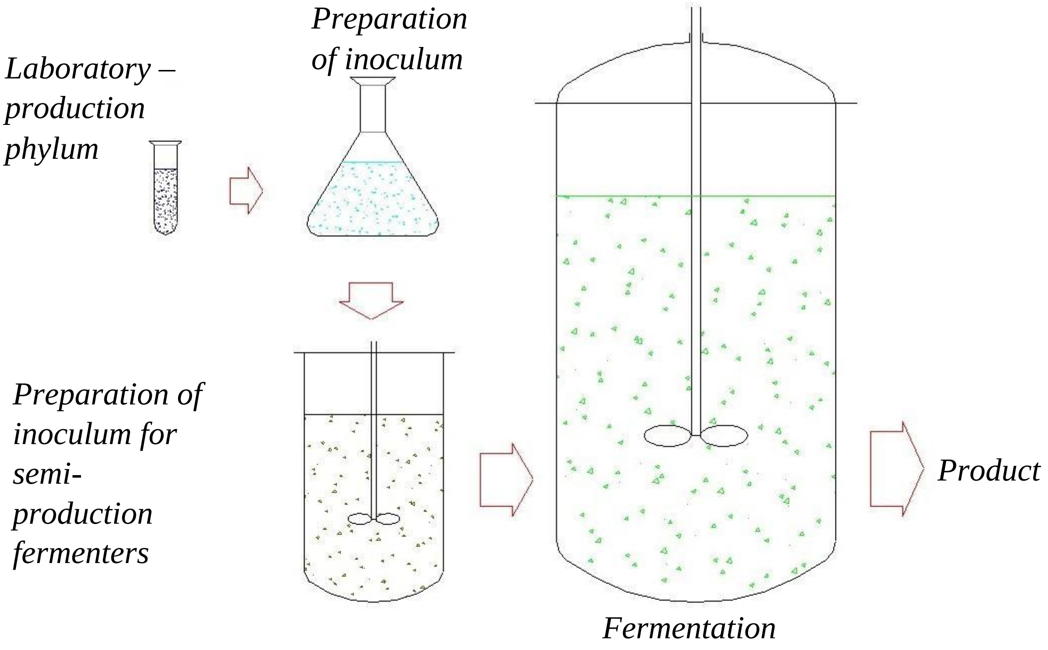


Fig. 13.15. Process fermentation [18]

ISOLATION OF CELLS AND METABOLITES (PRODUCTS)

It is necessary to separate biomass from the products after the end of the fermentation process. This is done using either centrifuges or filters. Other methods, for example precipitation, crystallization and the like, may also be used.

FURTHER PROCESSING OF BIOMASS AND PRODUCTS

If the main product is biomass, water must be removed from it by drying or evaporation.
An extreme case of vacuum drying is lyophilisation, in which water from the dried frozen material is sublimated at pressures around 1 Pa and temperatures around -20 °C at the beginning of the process and up to 30 °C at the end by post-drying. Products prepared by this method are almost 100 % rehydratable, preserve their original shape, and have excellent sensory properties.

Most biochemical processes require a certain degree of microbiological purity, which is achieved by processes of sterilization, decontamination, sanitation, and others.

Defining the driving force of bioprocesses is not easy. Many mutually affecting factors impact on it. The following simplified processes can be mentioned:

- *reaction with microorganisms* – the driving force is the potential of the microorganism, in relation to the nutrients (substrate) and oxygen, to create a definite product,

- *enzyme reaction* – the driving force is the biochemical potential of the enzymes in the given environment.

DIVISION OF BIOPROCESSES

ACCORDING TO THE GOAL OF PRODUCTION

- production of biomass as the main product (yeast...) or as a source for the isolation of other materials (enzymes, coenzymes...),
- production of primary (citric acid...) and secondary metabolites (molecules produced by an organism that does not have a main function in living processes, but may be important for a certain organism),
- transformation, i.e. chemical changes of organic molecules without a substantial change in their skeleton (simple enzyme reactions).

So it is possible to divide products into the following types of bioprocesses:

- natural metabolite (end product),
- enzyme –overproduction of a biologic catalyser,
- biologically useful material (antibiotics, vitamins),
- biomass – proteins, nucleic acids, polysaccharides,
- biomass isolate,
- active biomass (yeasts, decontamination, immobilization).

ACCORDING TO CATALYSER

- cultures or suspended cells of animals, plants and microorganisms (bacteria, cyanobacteria, algae, fungi...),
- isolated enzymes in a solution or bonded (immobilized).

ACCORDING TO RELATION TO OXYGEN

- anaerobic fermentation (fermenting of alcohol),
- aerobic fermentation:
  - submersed (cultivation of bacteria and yeasts),
  - surface (moulds – antibiotics, acids),
- in special reactors (immobilized cells).

ACCORDING TO TEMPERATURE

- • psychrophilic (under 20 °C),
- • mesophilic (20 – 40 °C),
- • thermophilic (over 60 °C).

ACCORDING TO PRODUCTION METHOD

- periodic (batch),
- semi-continual,
- continual:
  - continual addition of cultivation media, substrate, at the same rate (chemostat principle),
  - the substrate is added according to the growth rate of the biomass (turbidistate principle) in accordance with the intensity of the metabolism, e.g. consumption of oxygen or change of pH (metabolism principle).

These processes may be combined as multi-stage or work with biomass recirculation.

ACCORDING TO CULTIVATION METHOD

- cultivation on carriers (acetic fermentation),
- on the surface of a liquid or solid phase (semi-dry cultivation),
- immersed in media (submerged processes).

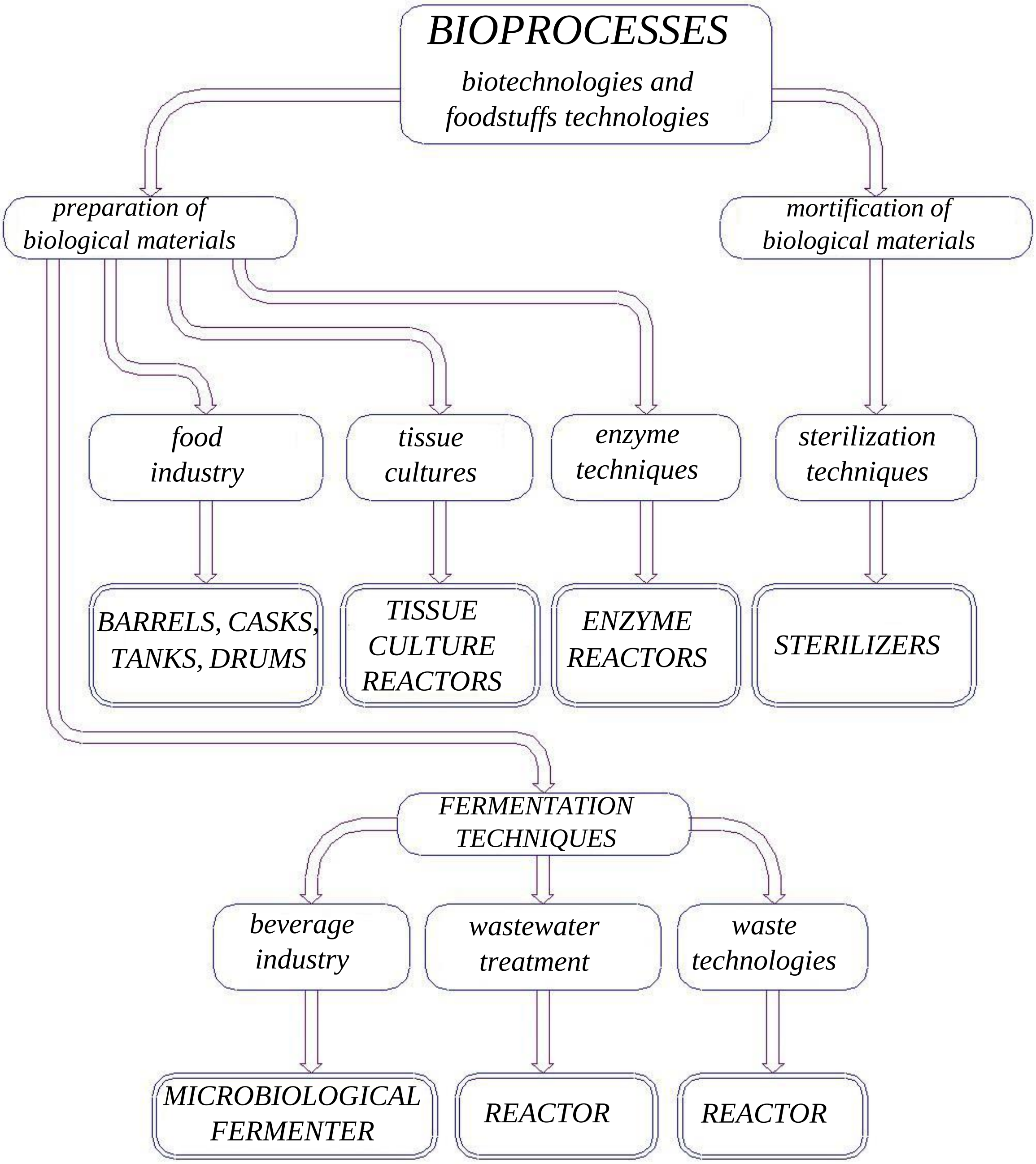


Fig. 13.16. Division of bioprocesses and fermentation technologies [18]

CALCULATION PRINCIPLE

The task of bioengineering is to mathematically describe the events taking place in bioreactors by equations known from the theory of transport phenomena (phenomena and processes related to the transfer of momentum, heat and material) and to provide practice with these bases for the design of the main dimensions of a bioreactor.

BASIC PROCESS PARAMETERS AND MEASURABLE PROCESS QUANTITIES

- bioreactor`s volume,
- initial composition of production media, concentration of individual components substrate at the beginning of the process,
- phylum of microorganisms and their concentration in production media at the beginning of the process,
- method of bioreactor operation in relation to oxygen,
- composition of the gaseous phase fed into a bioreactor,
- optimal value and course of change in pH production media,
- temperature of production media,
- mixer rotations (in the case that the load is mixed),
- redox process,
- concentration of gases on exit from bioreactor, e.g. CO_2,
- creation of foam in the course of the process,
- actual concentration of biomass, substrates, products,
- actual values of pH and redox, consumption of acids and bases for optimizing pH value,
- pressure, primarily atmospheric,
- method of feeding substrate into production media.

METHODS OF DESCRIBING AND INFLUENCING BIOPROCESSES

- mathematical deterministic models,
- empiric and statistical models.

The microbial mass may be either flake-shaped or a film adhering to supporting surfaces. In figure 13.17 is depicted and illustrated a heterogeneous model of a bioprocess with flake-shaped cell aggregates of large dimensions.

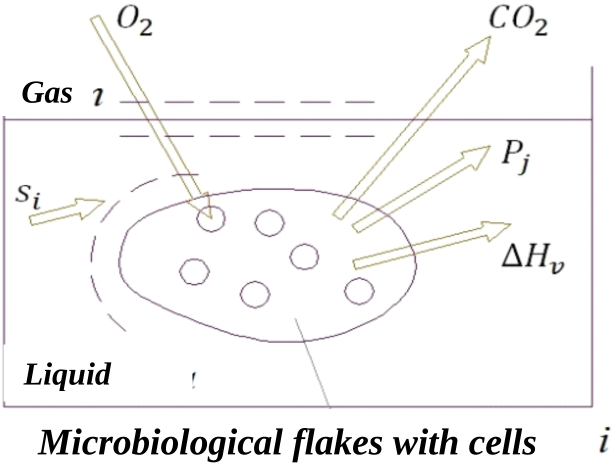


Fig. 13.17. Model of heterogenous process [18]

The entire process can be described in a general form:

$$s_i + O_2 + x_i \xrightarrow{T,p,pH} s_e + x_e + CO_2 + P_j + \Delta H_v \tag{13.1}$$

where

s_i – substrate concentration at the beginning $(\mathrm{kg.\,m^{-3}})$
x_i – biomass concentration at the beginning $(\mathrm{kg.\,m^{-3}})$
s_e – substrate concentration at the end $(\mathrm{kg.\,m^{-3}})$
x_e – biomass concentration at the end $(\mathrm{kg.\,m^{-3}})$
P_j – metabolic product concentration $(\mathrm{kg.\,m^{-3}})$
ΔH_v – amount of released heat $(\mathrm{J.\,m^{-3}})$

From the viewpoint of reactor balance, the consumption of the substrate by the microbial mass is crucial. It is defined by the yield coefficient, which is in turn defined as the relation of the emerging amount of cells to the consumed substrate:

$$Y_x = -\frac{\mathrm{d}x}{\mathrm{d}s} \tag{13.2}$$

It can be shown that if the external conditions are constantly maintained in the bacterial culture, the yield coefficient too will remain constant. The emerging amount of biomass will then be:

$$x - x_i = Y_x(s_i - s) \tag{13.3}$$

Other significant concepts are:

- the speed of biomass growth in the time defined by the Mond equation:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \mu\, x = r_x \tag{13.4}$$

- growth speed:

$$\mu = \frac{\mu_{max}\, s}{s + K_s} \tag{13.5}$$

where

K_s – constant of saturation $(\mathrm{kg.\,m^{-3}})$

- speed of substrate saturation, which is related to biomass concentration:

$$r_s = \frac{\mathrm{d}s}{\mathrm{d}t} = -R\, x \tag{13.6}$$

where

R – metabolic coefficient, specific speed of substrate consumption $(\mathrm{s^{-1}})$

- the product yield from the substrate, which represents the amount of product corresponding to a unit of the consumed amount of substrate:

$$Y_{P/s} = -\frac{\mathrm{d}P_j}{\mathrm{d}s} \tag{13.7}$$

- speed of product formation:

$$r_P = \frac{\mathrm{d}P_j}{\mathrm{d}t} \tag{13.8}$$

- speed of oxygen consumption:

$$r_O = \frac{\mathrm{d}O_2}{\mathrm{d}t} \tag{13.9}$$

- speed of emergence of CO_2:

$$r_{CO2} = \frac{\mathrm{d}CO_2}{\mathrm{d}t} \tag{13.10}$$

- speed of production of metabolic energy:

$$r_{\Delta h} = \frac{\mathrm{d}h}{\mathrm{d}t} \tag{13.11}$$

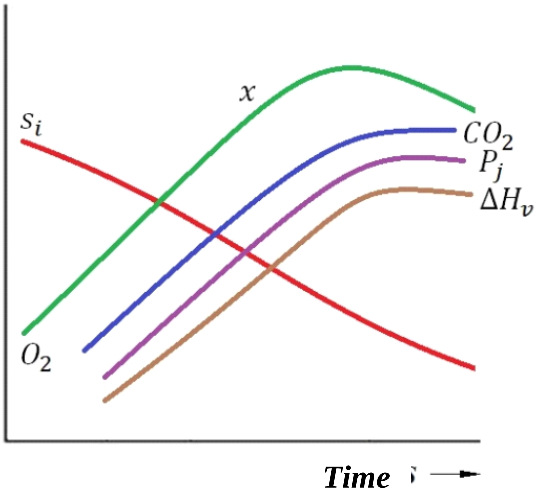


Fig. 13.18. Time course of individual parameters [18]

The modeling method is used in the design of bioreactors. Generally, laboratory testing is carried out in a small lab reactor, and from the results measured in this model are designed the dimensions of an operational reactor with the help of various criteria and calculations. While laboratory reactors have a volume of a few litres up to tens of litres, functioning reactors have volumes in the order of several hundreds to thousands of litres. A reactor consists of a cylindrical vessel of a height greater than its diameter.

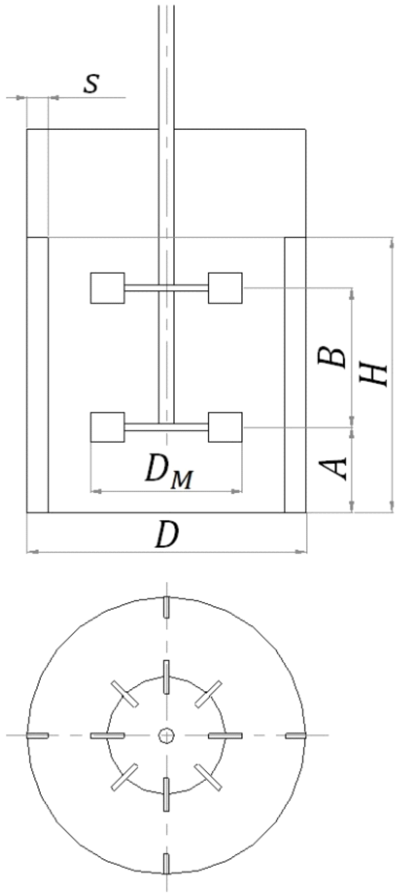


Fig. 13.19. Main dimensions of a bioreactor [18]

In calculating the dimensions for an operational reactor, the starting point is the dimensions from the laboratory reactor and the maintenance of the following proportional dimensions:

- the relation below is important data for the work of a reactor, since it influences the efficiency of aeration and mixing:

$$\frac{H}{D} = 1{,}0 \tag{13.12}$$

For the relation $H/D < 1$ a simple mixer is used; if the relation is up to 2, a double mixer must be used.

- other criteria:

$$\frac{D_M}{D} = 0{,}34 \tag{13.13}$$

$$\frac{A}{D_M} = 0{,}8 - 1{,}0 \tag{13.14}$$

$$\frac{B}{D_M} = 1{,}0 - 1{,}2 \tag{13.15}$$

$$\frac{s}{D_M} = 0{,}08 - 0{,}1 \tag{13.16}$$

When designing the power for a mixer, it is based on the relationship:

$$P = Eu_M \,\rho\, n^3 \, D_M^5 \tag{13.17}$$

And the Euler number for mixing can be written in the form:

$$Eu_M = \frac{P}{\rho\, n^3\, D_M^5} \tag{13.18}$$

The Reynolds number for mixing determines the flow character in a reactor during the mixing process:

$$Re_M = \frac{n\, D_M^2}{\nu} \tag{13.19}$$

The relation between the Reynolds and the Euler numbers is determined experimentally for the various types of mixers. In figure 13.20 is shown a diagram for a turbine mixer with straight blades.

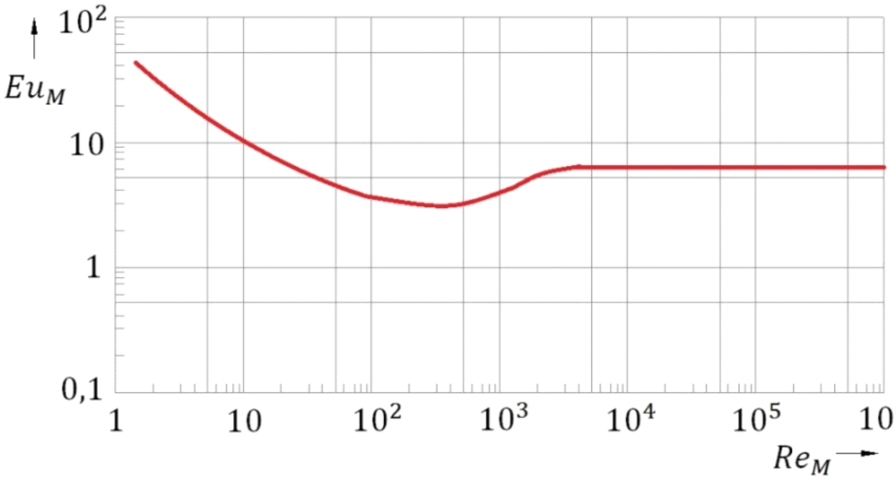


Fig. 13.20. Diagram for determining the relation between the Reynolds and the Euler numbers for a turbine mixer with straight blades [18]

Aeration systems are usually used in the fermentation industry. In such cases, the mixing force is significantly lower. This is caused by a drop in the density of the liquid as a result of the presence of air bubbles. This drop is in the vicinity of 0,3 – 1,0 in dependence on the type of mixer. The power necessary for an aeration system can be determined from the equation:

$$\frac{P_g}{P} = f(Na) \tag{13.20}$$

This relation is determined experimentally for various aeration numbers and mixer shapes. An example of such dependence is illustrated in figure 13.21.
The aeration number is defined as:

$$Na = \frac{\dot{Q}}{n\, D_M^3} \tag{13.21}$$

where

$\dot{Q}$ – the flow of air to the fermenter $(\mathrm{m^3.s^{-1}})$

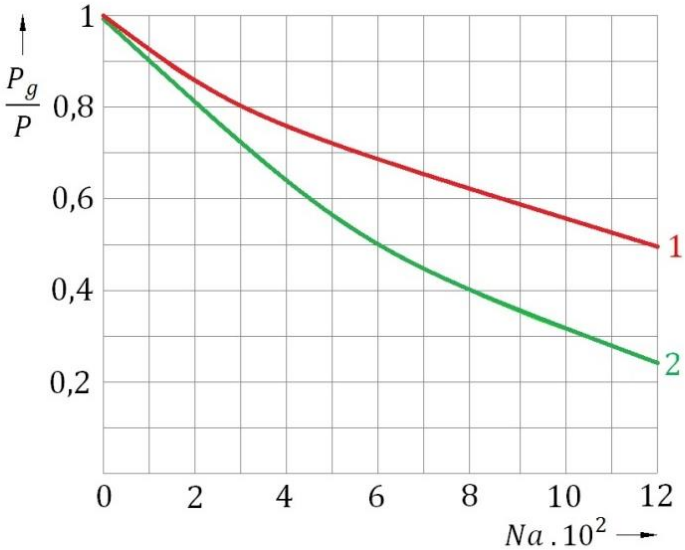


Fig. 13.21. *Diagram for determination of the aeration number [18]:*
1 – turbine mixer with eight straight blades, 2 – turbine mixer with six curved blades

APPARATUSES

The basis of biotechnology is a group of processes focusing on cultivation, fermentation and biochemical changes carried out in cultivation equipment or in bioreactors. Apparatus construction must meet the demands of production cultures and the character of the process. Well-mixed ingredients must be provided and, in the case of aerobic bioreactors, good dispersion and a sufficient flow of oxygen.

For these reasons, reactors are almost exclusively made of stainless steel or glass. The entire process requires quite strict regulation and management regimes.

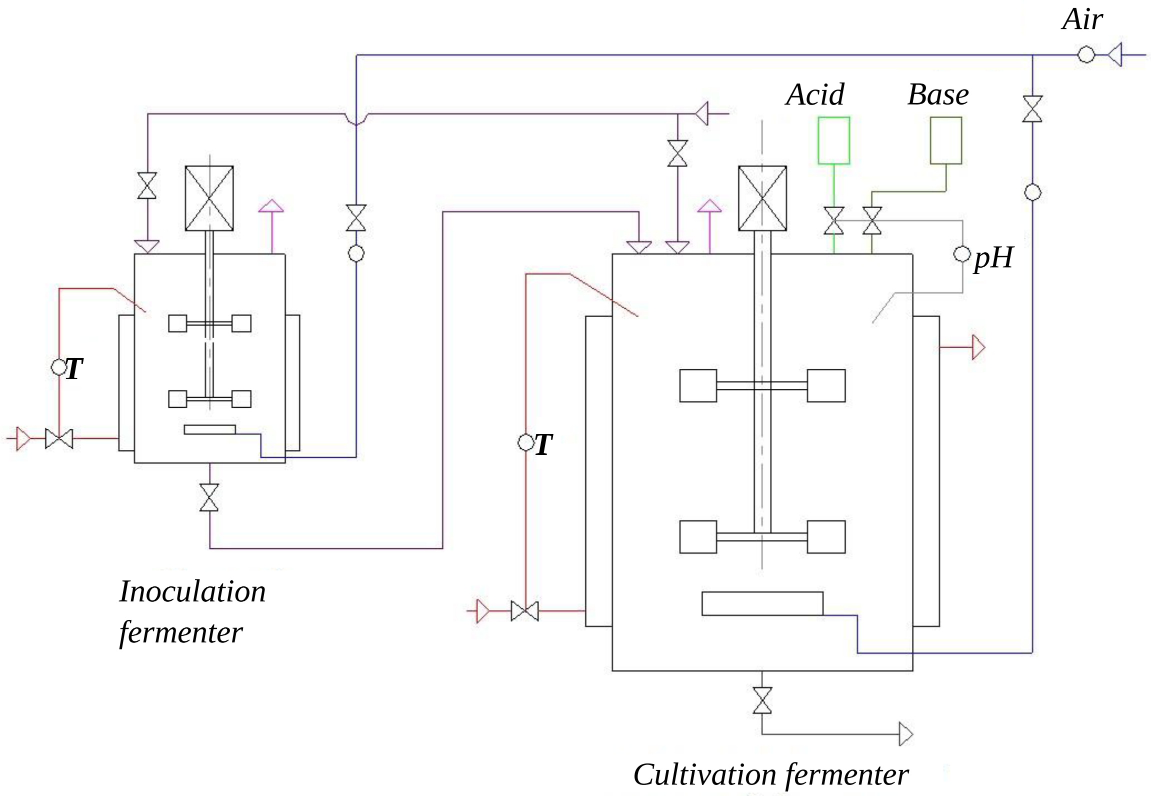


Fig. 13.22. Scheme of the arrangement of an inoculation and cultivation bioreactor [18]

Fig. 13.23. Real equipment of a station with an inoculation and cultivation bioreactor [48]

A reactor may function as:

- *a batch reactor*

  Under perfect mixing, such a reactor does not have local concentration gradients. It is essentially a vessel with a mixer. This type of reactor is used as both an inoculation and production apparatus, with volumes of from a hundred to a thousand litres. The time for batch fermentation may be several hours but also weeks, in dependence on the batch conversion and working conditions. During the whole of this time contamination must be avoided, the contents of the vessel must be well-mixed, and its temperature regulated. To ensure aseptic work, it is necessary to sterilize the nutrient solution (substrate), the reactor vessel itself, and also the accessories. The effect of the mixer in the reactor is most complicated. Above all, the microorganisms in the substrate must be well-mixed and, with aerobic fermentation, the added air must be dispersed in the form of bubbles.

  The design of such a reactor takes into consideration the dimensions of the vessel, the duration of the given process, the initial substrate concentration and the area for the heat exchange. Different theories of similarity are used for this, but still the design of the reactor is complex and depends on the designer's skill and experience. The most widespread type of batch reactor is the mechanically mixed reactor with baffles. Usually the air is added under the mixer and the distributor separates it into light bubbles. During these processes, foam forms in the reactor due to the presence of metabolites with surface active properties. The foam is not wanted and so various foam-removing agents (natural and mineral oils, fatty acids and the like) are added into the reactor.

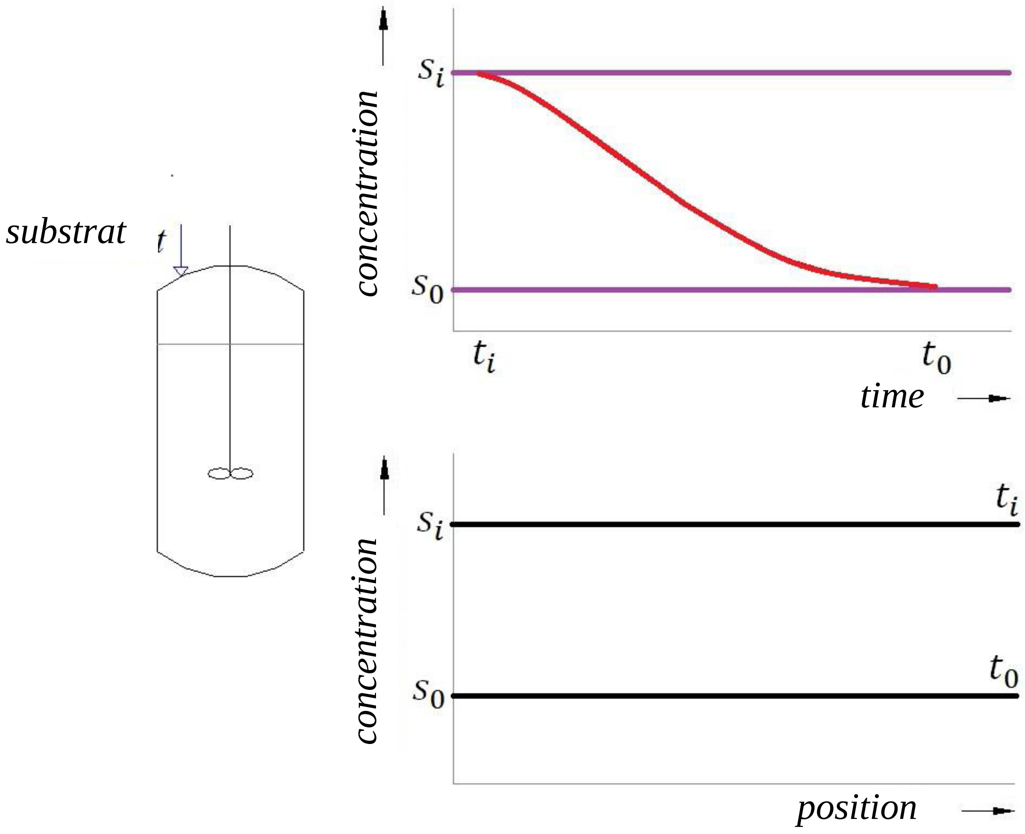


Fig. 13.24. Time and local dependence of substrate concentration in a batch reactor[18]

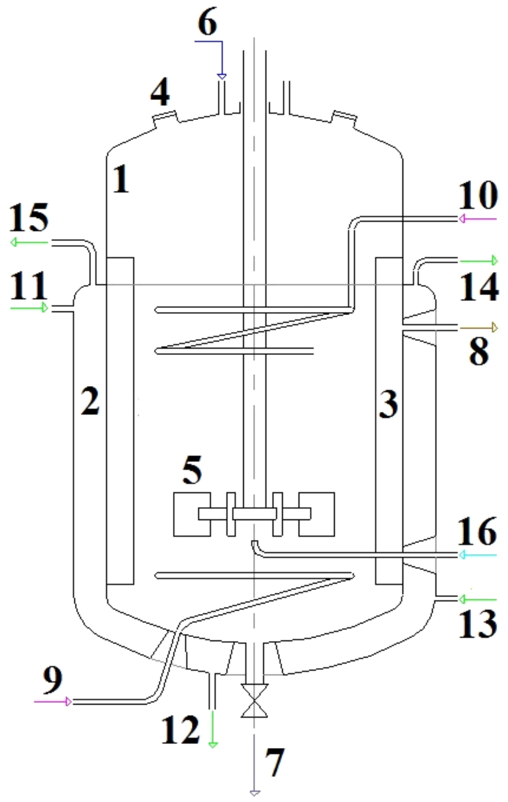


Fig. 13.25. Scheme of a batch reactor [18]:
1 – reactor vessel, 2 – duplicator, 3 – baffles, 4 – opening for connection of a probe, 5 – mixer, 6 – input of inoculate, 7 – drain, 8 – sampler, 9 – inflow of water into heating tube (drainage of condensate from heater), 10 – outflow of water from heating tube (inflow of steam into heater), 11 – input of steam, 12 – outflow of condensate, 13 – inflow of water, 14 – outflow of water, 15 – venting, 16 - gas phase input

Fig. 13.26. Example of a working laboratory batch reactor [48]

- semi-continual (repeated) fed-batch reactor

  The reactor is filled to a given level and inoculated with the inoculum. During the course of cultivation, a loss of substrate is caused due to its consumption by microorganisms. This loss is replaced by the periodic addition of fresh substrate.

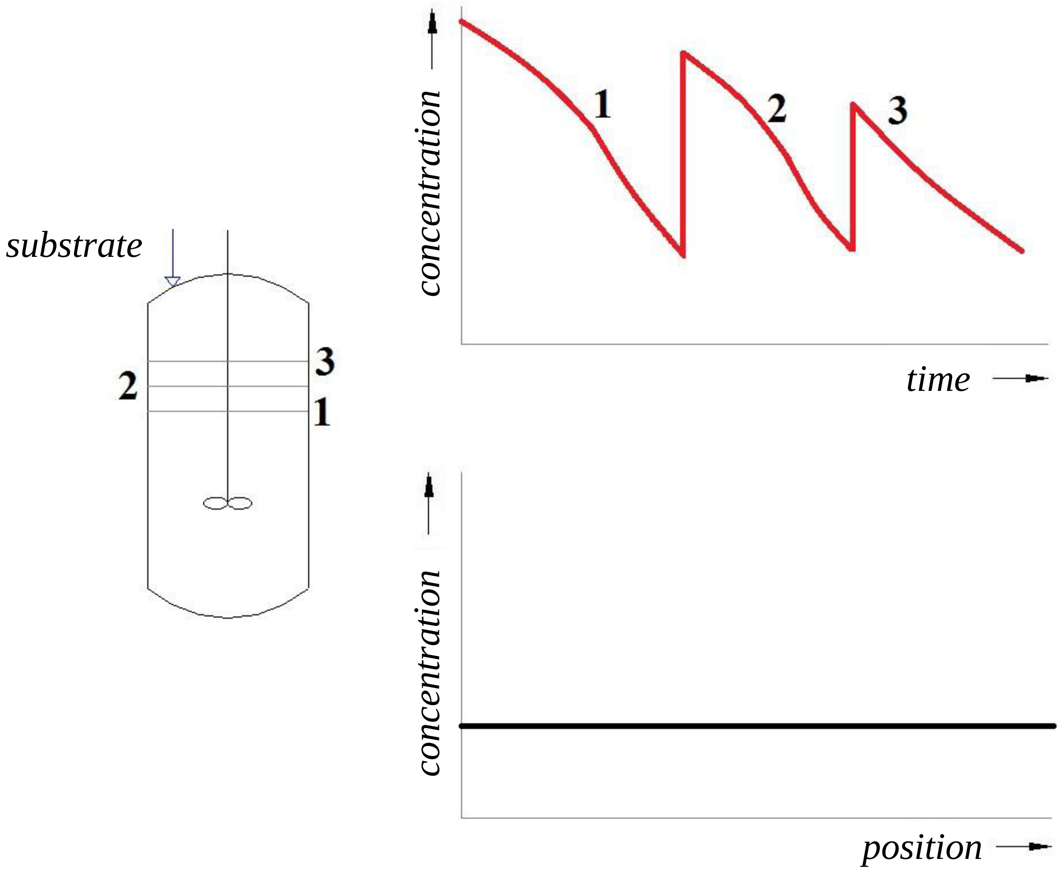


Fig. 13.27 Time and local dependence of substrate concentration in a batch reactor with the periodic addition of substrate [18]

- continually stirred tank fermenter

  This reactor works similarly to the batch model, but with the difference that it has an injection and overflow (drain) section. The continual reactor is in a permanent state, which means that the retention of microorganisms and concentration components of the nutrient media (substrate) in the reactor are constant. Continually stirred reactors often operate in a cascade arrangement. Continual processes are successfully managed in, for example, the production of baker’s yeast and microbial proteins, and in the purification of waste water.

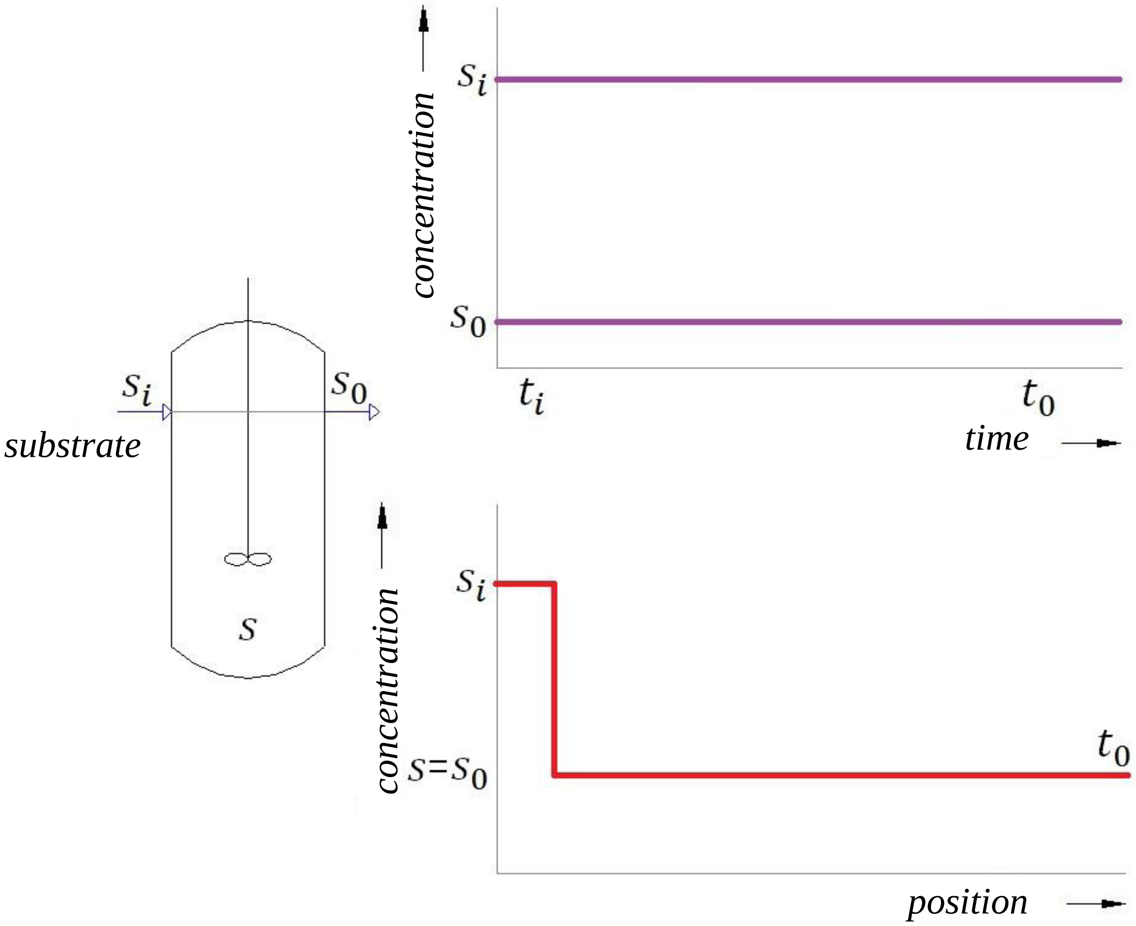


Fig. 13.28 Time and local dependence of substrate concentration in a fed-batch reactor[18]

The fed-batch reactor has the following advantages:

- reduction of operating expenses as a result of omitting operations connected with the filling, emptying and sterilization of the fermenter,
- greater scope for automatic operation,
- constant working conditions,
- continual regime providing equal conditions for all microorganisms, thus reducing the possible production of auxiliary products.

The environment in the reactor during its operation can create the following processes:

- *A homogeneous process* usually occurs only in the case of the usage of enzymes in a dissolved form. It can be assumed that the process happens mostly in the fluid phase. In the case of thorough mixing, there is no restriction of the contact of the substrate with enzymes or microorganisms.

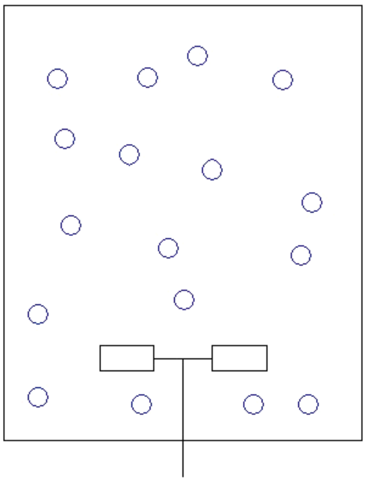


Fig. 13.29. Scheme of the homogeneous process [18]

- *A pseudo-homogeneous process* can be identified by biological flakes or with enzymes bonded in the shape of flakes. Clusters of microorganism cells in the shape of flakes create a solid phase in the liquid phase. In the case of small flake diameters and with ideal mixing, it can be assumed that there will be no restrictions to the transfer of substrate, either in the phases or between them.

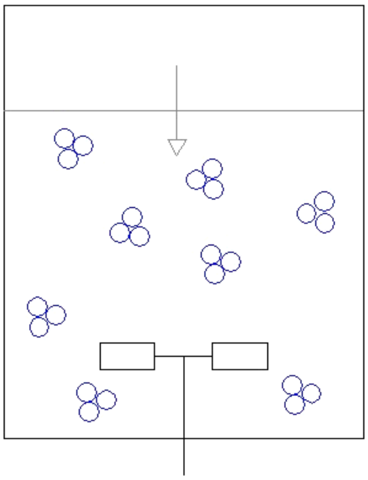


Fig. 13.30 Scheme of the pseudo-homogeneous process [18]

- *A heterogeneous process* occurs when the flakes have larger diameters or the microbial mass is in the shape of films or sediments that grow quickly. Here transport phenomena come to the fore, both in the reaction phases and between them.

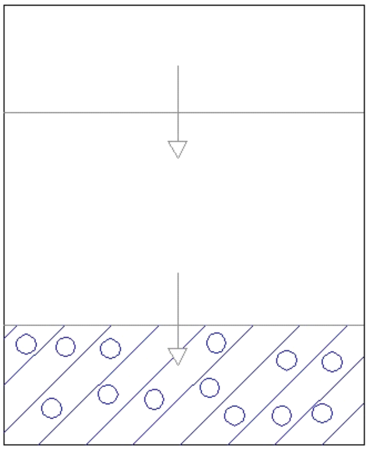


Fig. 13.3. Scheme of the heterogeneous process [18]

CONSTRUCTION DETAILS

- *Couplings*

  A mixer is placed in the vessel in either the upper or the lower part of the reactor. The is driven via magnetic couplings which allow maintenance of a sterile environment within the reactor. Magnetic couplings allow power transmission of up to 20 kW.

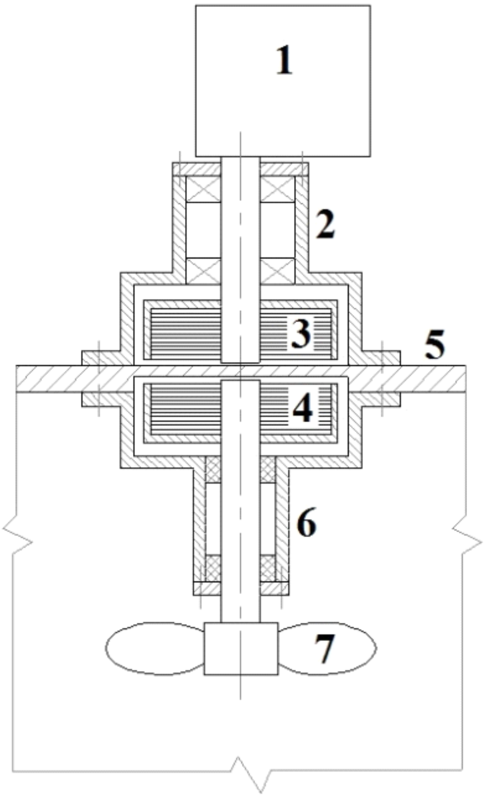


Fig. 13.32 Mixer drive by axial magnetic coupling [18]:
1 – motor, 2 – bearing housing, 3 – drive part of magnetic coupling,
4 – drive part of magnetic coupling, 5 – lid, 6 – bearing housing,
7 – mixer

- *Mixer*
  Mixer shape and dimensions play an important role in the correct functioning of a reactor. In figure 13.33 are shown samples of various mixers. Mixers mix and homogenize the contents of the reactor. They also break up large air bubbles and thus intensify the flow of oxygen to the culture.

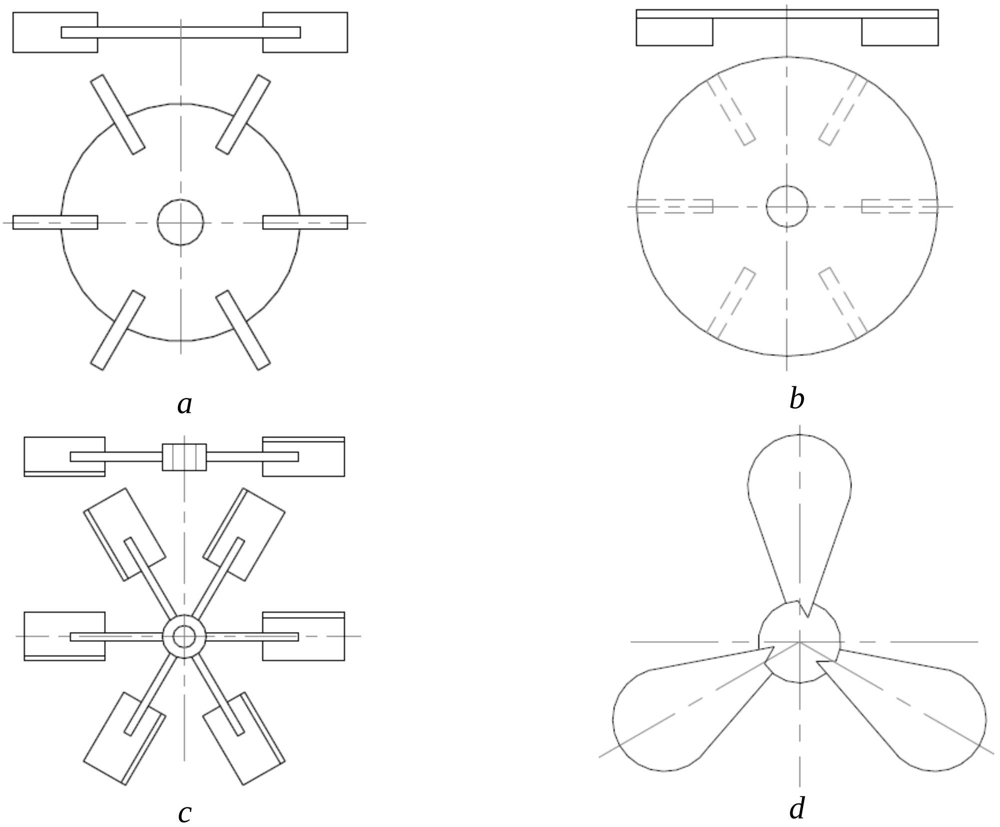


Fig. 13.33. Mixer types [18]:
a – turbine mixer with disc, b – turbine mixer with blades below disc, c – open turbine, d – screw mixer

A turbine mixer is made up of a disc on which usually 6 vertical blades are placed. A mixer has good homogenizing effects and also provides good dispersion of air. Mixers can also have the the shape of an open turbine, but such a setup has a reduced mixing effect. If the mixer has the shape of a ship's screw, it generally creates an axial fluid flow.

- *Air distributors*
  Their job is to gently and equally distribute the air in the reactor vessel. The air intake is situated either in the upper or lower flange. The safest type of separator is a pipe twisted into a ring that has openings drilled on the top side. Bubbles flow between the mixer blades, which make them even gentler by breaking them into smaller diameters.
  In addition to the above- mentioned methods of mixing, there also exists for example a bioreactor which mixes by forced air, the so-called *airlift*. Circulation here takes place as a result of the density differences in the individual sections of the reactor.

If the airlift has an internal circuit, this is made up of an internal (central) pipe, an external pipe, an air distributor, and the appertaining sensors. Air is fed into the central pipe and the differences in infill densities in the central pipe and the intermediate annulus cause the circulation of the fluid content of the reactor.

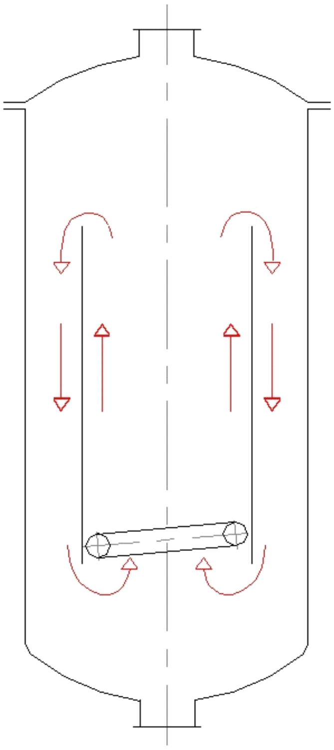


Fig. 13.34. Schematic illustration of airlift bioreactor [18]

INDUSTRIAL APPLICATIONS

Biotechnologies mostly deal with the research, development and production of materials which are suitable substrates for microbial growth, and the subsequent production of chemicals important for industry. These include, for example, the production of biochemicals in the antibiotics industry (penicillin...), foodstuffs production in the dairy industry, the preparation of drinks in the beer, wine and spirits industries, biological processes for the cleaning of waste water, and more.

The future of biotechnologies lies in the preparation of substances that are difficult to manufacture on an industrial scale in purely physical-chemical ways (e.g. citric acid– conservation industry, production of non-alcoholic beverages...) or which are today manufactured in the petrochemical industry (e.g. acetone, which can be produced by fermentation).

In addition to production, there are also cleaning technologies. Here the main product is purified water, with as an auxiliary product biomass (activated sludge), its components, or metabolites (methane).

Fig. 13.35. Bioreactor [48]

Among the industrial applications of biotechnologies can be listed:

- biological methods for removing mercury from contaminated soil and waste water by bio-transformations using bacteria,
- removing heavy metals from contaminated soil,
- biological detoxification of soils with oil components,
- degradation of certain types of aromatic hydrocarbons through the use of oxidation methods,
- removing foreign materials, detergents and bleaches from waste water,
- biological neutralization of organic components from solid waste and old waste deposits,
- soil recultivation,
- deactivation of waste water through the use of granulated sludge from waste water in the process of methane fermentation,
- usage of waste water from dairies,
- biological and thermal methods of liquidation of solid wastes, and sludge from waste water.

At the end of the 20th century, NASA began developing equipment that would allow the study of mammalian tissue in a microgravity field. Such equipment makes it possible to study tissue, tumours and viruses outside the body, both on Earth and in space. Cell cultures grown in laboratories usually have a tendency to be small, flat and two-dimensional, as oppesed to other cultures. However, tissues grown in RCCS (Rotary Cell Culture System) are larger and three-dimensional.

RCCS is also used for the study of various infections and the Ebola virus, as well as being key in the development of vaccines for treating HIV.

A sealed cylinder is filled with liquid, in which cells of micro-dimensions grow. This chamber rotates along a horizontal axis and allows the cells to develop in an environment similar to free-fall or micro-gravity. The oxygen necessary for cell growth is added into the liquid through the perforated wall of the chamber.

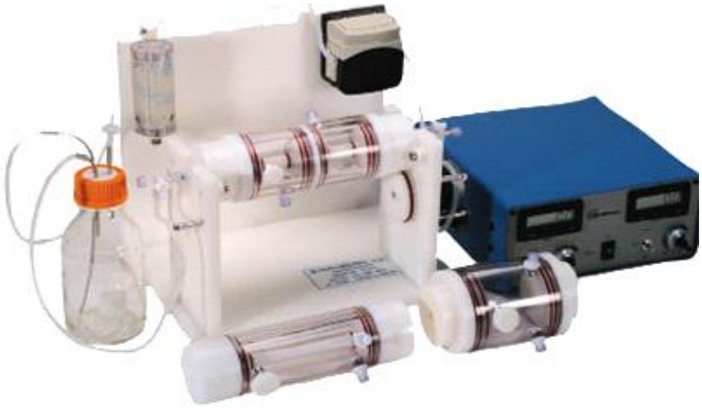


Fig. 13.36. NASA RCCS bioreactor providing weak turbulent flowing supporting the development of large, three-dimensional cell clusters [43]

The ‘landfill’ bioreactor brings about a significant change and degradation of organic waste. The increase in waste degradation is enhanced by the liquid and air that make the microbial process more effective.

The most important factor is humidity, which should be from 35 to 65 %. The presence of humidity, together with the biological effect of microbes, breaks down waste. A secondary effect is the emergence of gases, for example methane and carbon dioxide. Some studies point out the advantageous obtention of gases that are very suitable from an energy standpoint.

There are three different types of bioreactor:

- *Aerobic bioreactors*

  In “landfill” aerobic bioreactors, the filtrate is removed from the bottom layers and delivered by pipes to a tank, from where it is recirculated to the dump in a controlled manner. Air is supplied to the waste through horizontal or vertical drill-holes to support the aerobic activity.

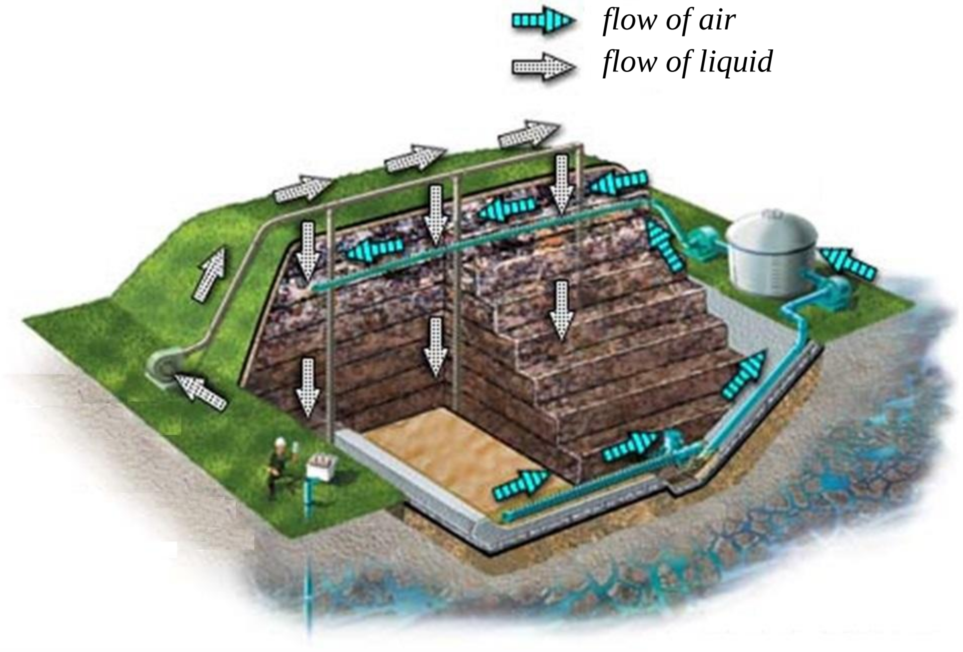


Fig. 13.37. "Landfill" aerobic bioreactor [44]

- *Anaerobic bioreactors*
  In these "landfill" bioreactors humidity is added into the waste in the form of a recirculated filtrate or other media for optimization of bioreactor functioning. Biodegradation takes place due to the absence of oxygen, and the produced gas, containing methane, is captured for the minimization of greenhouse gases and is also used as a source of energy.

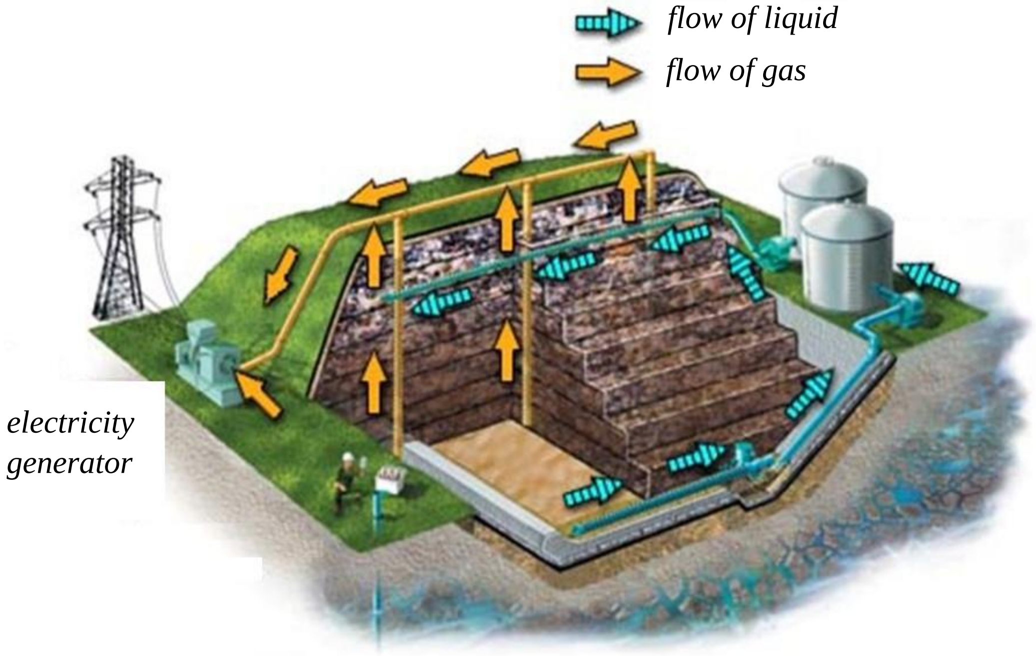


Fig. 13.38. "Landfill" anaerobic bioreactor [44]

- *Hybrid (aerobic - anaerobic)*
  This bioreactor speeds up the degradation of waste through the use of *aerobic - anaerobic* operation, with the degradation taking place in the upper part and gas collected below. This arrangement accelerates the production of methane.

LIST OF SYMBOLS

k_G	–	partial oxygen transfer coefficient in diffusion film layer	(1)
n	–	bioreactor mixer rotational frequency	(s^{-1})
p	–	pressure	(Pa)
r_s	–	substrate consumption rate	$(\mathrm{kg.\,m^{-3}.\,s^{-1}})$
r_x	–	biomass growth rate	$(\mathrm{kg.\,m^{-3}.\,s^{-1}})$
r_{CO2}	–	rate of carbon dioxide formation	$(\mathrm{kg.\,m^{-3}.\,s^{-1}})$
r_O	–	rate of oxygen consumption	$(\mathrm{kg.\,m^{-3}.\,s^{-1}})$
r_P	–	rate of product creation	$(\mathrm{kg.\,m^{-3}.\,s^{-1}})$
$r_{\Delta h}$	–	rate of metabolic energy creation	$(\mathrm{J.\,m^{-3}.\,s^{-1}})$
s	–	actual substrate concentration	$(\mathrm{kg.\,m^{-3}})$
s_e	–	final substrate concentration	$(\mathrm{kg.\,m^{-3}})$
s_i	–	initial substrate concentration	$(\mathrm{kg.\,m^{-3}})$
$\check{s}$	–	width of bioreactor baffles	(m)
t	–	time	(s)
x	–	actual biomass concentration	$(\mathrm{kg.\,m^{-3}})$
x_e	–	final biomass concentration	$(\mathrm{kg.\,m^{-3}})$
x_i	–	initial biomass concentration	$(\mathrm{kg.\,m^{-3}})$
A	–	height of the bioreactor agitator separator disc from the bottom of the bioreactor	(m)
B	–	height between the separating rings of the bioreactor mixer	(m)
D	–	diameter of the bioreactor vessel	(m)
D_M	–	diameter of the bioreactor mixer separator disc	(m)
Eu_M	–	Euler number for mixing	(1)
H	–	height of the bioreactor vessel	(m)
K_s	–	constant of saturation	$(\mathrm{kg.\,m^{-3}})$
Na	–	aeration number	(1)
P	–	power of the bioreactor mixer	(W)
P_g	–	power of the aerated bioreactor agitator	(W)
P_j	–	concentration of the metabolic product	$(\mathrm{kg.\,m^{-3}})$
$\dot{Q}$	–	air flow through the fermenter	$(\mathrm{m^3.\,s^{-1}})$
R	–	metabolic coefficient, specific rate of substrate consumption	(s^{-1})
Re_M	–	Reynolds number for mixing	(1)
T	–	temperature	(K)
$Y_{p/s}$	–	yield product from substrate	(1)
Y_x	–	yield coefficient	(1)
δ_G	–	layer thickness for diffusion from the main gas stream to the gas-liquid interface	(m)

δ_{L1} – the thickness of the layer during diffusion through the boundary layer into the mainstream of the liquid (m)
δ_{L2} – the thickness of the layer during diffusion through the boundary layer to the surface of the microbial particles (m)
μ – growth rate (s^{-1})
μ_{max} – maximum growth rate (s^{-1})
ν – kinematic viscosity of the stirred substance $(\mathrm{m}^2.\mathrm{s}^{-1})$
ρ – density of the stirred substance $(\mathrm{kg}.\mathrm{m}^{-3})$
ΔH_v – amount of heat released $(\mathrm{J}.\mathrm{m}^{-3})$

14 SAFETY ENGINEERING

With the current rapid development of the chemical industry worldwide and the increasing efficiency of production, it is becoming ever more important to place greater emphasis on ensuring safety in chemical operations in order to prevent the occurrence of a significant industrial accident. In a wider context, the concept of safety can also express the avoidance of losses of health and life, damage to property, production output and the environment.

Pursuant to Act no. 128/2015 Z. z. on the Prevention of Major Industrial Accidents, selected basic concepts of safety engineering can be defined as:

- *Operation* is the whole complex under the administration of the same operator in which a given hazardous material is present in one or several premises, including common or related infrastructures and activities;
- *Premises* is a technical or technological unit in which a given hazardous material is produced, processed, used, transported, stored or otherwise handled;
- *Major industrial accident* is an event such as above-limit emissions, fire or explosion with the presence of one or more hazardous materials as a result of uncontrolled developments in the premises of any of the enterprises concerned by this Act. These can directly or subsequently lead to significant damage or threat to the life or health of persons, the environment, or property within the premises or outside it;
- *Prevention* of a major industrial accident is a set of organizational, management, personnel, technical, technological and material measures for the prevention of the occurrence of a major industrial accident;
- *Accident plan* is documentation comprising the set of technical, organizational and other measures prepared for dealing with a major industrial accident and for limiting its consequences on the premises of an enterprise;
- *Hazard* (source of the risk of a major industrial accident) is the internal property of a given material or a physical situation with the potential to endanger human health, the environment, or property;
- *Risk* of a major industrial accident is the probability of the occurrence of a major industrial accident and the extent (seriousness) of the potential consequences that may occur during a certain period or under certain circumstances;
- *Safety report* is documentation comprising the technical, administrative and operating information on hazards and risks of a category B enterprise and on measures for their prevention or reduction.

QUALITY METHODS FOR IDENTIFYING HAZARDS

DOW INDEX METHOD

The Dow index method is a screening method suitable for the rapid determination of an operations unit's hazard level. It is made up of two indexes:

- *Fire/explosion index (FEI)*

Expresses the extent of a hazard related to the physical-chemical properties of a material and to the system's technical infrastructure.

- *Toxicity index (TI)*

Expresses the extent of a biological hazard resulting from the toxic properties of materials in the investigated operations unit.

First it is necessary to divide the investigated operation into individual units, which will be considered independently. By the term ‘unit’ is understood premises in which individual operations of a physical or chemical nature are carried out. For each investigated unit, the individual fire/explosion index and the toxicity index are determined.

The *FEI* value is dependent on three quantities - the material factor, the general process factor and the special process factor. According to the calculated *FEI* values of each unit, a degree of threat of fire or explosion is assigned (1 – low degree..., 6 – extremely high degree).

The *TI* value is a function of the toxic properties of the material and the penalty factors (1 – low degree..., 6 – extremely high degree).

From the calculated *FEI* and *TI* factors, the investigated unit is classified into the index matrix and a transparent ranking of the premises is created.

This risk evaluation method can relate to risks associated with the handling of chemical materials and chemical industry processes for units that handle or process more than 2000 kg of combustible or explosive material.

SELECTION METHOD

The selection method is based on the calculation of *indication number A* and *selection number S*. These numbers serve for the selection of a company’s risk prone premises in which it is necessary to carry out more detailed evaluations of risk assessment. The indication and selection numbers are calculated in dependence on the amount of the given hazardous materials, their properties, and the conditions where they are located. The riskiness of the investigated premises is also determined on the basis of their distance from selected buildings and facilities.

The procedure for risk evaluation according to the selection method can be divided into the following steps:

- *division of a company into its operations units*

  As an independent operations unit can be considered such a unit for which the loss of the contents of the given unit due to fire does not cause significant loss of the contents of other units, and which can be isolated in a very short time after the outbreak of a fire. Within the selection method two types of premises are identified – processing and storage premises.
- *calculation of indication number A*

  This indication number is calculated as the degree of internal hazard of an operations unit. It depends on the amount of hazardous materials, their physical, chemical and toxic properties, and the specific operating conditions in the investigated operations unit.
- *calculation of selection number S*

  Calculation of the selection number for an investigated unit results from the indication number of the unit, characterised by its hazardous properties - combustibility (F), toxicity (T) and explosiveness (E). The calculated selection numbers also depend on the distance of the operations unit from the investigated complex.
- *selection of the most hazardous operations units*

  From the result of these steps are created selection number tables, with each number relating to the hazardous property of the operational unit’s materials and to the complex under inspection. Then the selection numbers of the operations units for each given object are compared, and the highest selection number for each object is picked.

INSPECTION REGISTER METHOD

The inspection register method is based on the creation and application of specific tools focused on the identification of hazards, project insufficiencies, and technological problems related to equipment, lines and the processes themselves. The process of identification of a hazard can be divided into the following steps:

- *creation of an inspection register*
  To create an inspection register it is necessary to have at the inspector`s disposal documentation containing information on equipment, working procedures, safety standards, procurement, production phases and operational parameters of the processes. The questions must be formulated such that the answers to them are brief – such as yes, no, inapplicable.
- *analysis design*
  In the analysis design phase, it is important to answer prepared questions from the inspection register.
- *results of analysis*
  A safety analysis report by the inspection register method must also contain, in addition to the relevant questions, a summary of the insufficiencies which were identified during the analysis.

WHAT IF METHOD

In the ‘what if’ method, a team of specialists considers a selected operation from the standpoint of the emergence of possible hazardous states through questions which begin with the phrase ‘What if…’ The stated method can be used at any stage of the process’s lifecycle.
The process of identifying a hazard can be divided into the following steps:

- *preparation of What if...? questions*
  Preparation involves gathering documentation containing information on the process, equipment, raw materials, operations procedures, safety standards and legal regulations. The preparation of questions results from experience with other similar operations.
- *analysis design*
  The analysis is based on asking the created questions. The procedure of the individual technological operations runs logically from the input of raw materials into the operation to the output of products from the production line.
- *results of analysis*
  The report of the safety analysis through the What if…method contains, in addition to the answered questions, a list of insufficiencies and their results, and suggested counter-measures. The documentation should also contain recommendations for improving safety.

HAZOP METHOD

In contrast to the preceding methods, HAZOP (Hazard and Operability study) is a systematic method determined for the identification of potential errors in equipment and operations that could lead to hazardous situations. At present, the HAZOP method is the most widely-used method for identifying hazards in industrial operations. Its main goal is the identification of hazards and making critical reviews of all processes and procedures.
The principle of the HAZOP method is to identify potential deviations from the project`s original intention, to find the reasons for them and their possible consequences, and in the final analysis to propose measures for preventing the occurrence of faults and reducing the negative outcomes of these deviations.

The HAZOP method can be divided into the following steps:

- *defining the project`s intended functioning for selected parameters*
  Even before defining the project`s original intention for selected parameters, it is necessary to divide the assessed unit into smaller units – clusters that are logically related to each other and which have characteristic parameters. After choosing the individual clusters for a selected parameter, the next step is to define the specific value that is desired for the given parameter. This parameter can be indicated by operating conditions, e.g. temperature, pressure, flow, level, conductivity, concentration and others.
- *creation of deviations from the original intention by application of a key word*
  The creation of a deviation from a project`s intention takes place by connecting the selected parameter with key words. For the sake of systemization, it is necessary to create all the logical combinations of the parameter with a key word, such as:
    - **no, none** (complete negation of the intention),
    - **more** (quantitative increase),
    - **less** (quantitative decrease),
    - **as well as** (qualitative increase),
    - **part of** (qualitative decrease),
    - **opposite** (logical negation of the intention),
    - **other than** (complete exchange).
- *searching for the reasons for the deviation*
- *searching for the consequences of the deviation*
- *proposal of measures*

QUANTITATIVE-QUALITATIVE METHODS FOR IDENTIFICATION OF HAZARDS

FAULT TREE ANALYSIS

Fault tree analysis is a deductive method determined for the identification of circumstances from which a real accident can occur. The analysis uses a graphic diagram that illustrates the reasons that can lead to a serious system breakdown, a so-called peak event. The construction of the fault tree begins by defining the peak events and logical development of breakdowns that make up the causes of a peak event. The goals of the fault tree are:

- determination of the combinations of breakdowns of equipment, operating and environmental conditions, and human error,
- identification of measures that can increase dependability and safety,
- calculation of the number of accidents or the dependability of the equipment.

The procedure for working out a fault tree analysis consists of the following steps:

- defining the system,
- identification of a hazard,
- construction of the fault tree
- qualitative confirmation of a structure,
- quantitative assessment of the fault tree.

ANALYSIS OF A TREE OF EVENTS

Analysis of a tree of events is a graphic logic model that quantifies the potential consequences of events that belong in the fault tree. The tree of events illustrates a systematic time progression of the spreading of an event from the moment of origin of the initiating event to the complete loss of control over the system. The tree of events has two typical application areas:

- *before an incident*
  Check safety systems that serve to prevent the outbreak of an incident with hazardous consequences.

- *after an incident*
  Is used to quantify an incident's hazardous consequences. In the chemical industry, this refers primarily to incidents related to the escape of a hazardous material that could lead to a fire, explosion or toxic threat.

In constructing a tree of events, the starting point is the initial event, and then goes progressively through all the systems intended to prevent the occurrence of hazardous consequences. Each branch of the tree of events illustrates the consequences of the initial event.

ANALYSIS OF HUMAN RELIABILITY

The level of reliability of human performance is extremely important in the functioning of a system, and it can be divided into two groups:

- *internal factors*
  Here can be classed stress, emotional state, experience and personal preparedness.
- *external factors*
  Among external factors belong working period, work environment, management approach, and methodological procedures.

The internal and external factors are the basic sources of human error that may arise during normal operations. Today there exist special methods for the identification of dangers from human-equipment systems. A general analysis procedure consists of the following steps:

- description of the work environment, tasks and characteristics of personnel,
- evaluation of the person-technology interface,
- performance of task analysis of the individual functions of workers,
- performance of human error analysis of the individual functions of workers,
- documentation of results.

An analysis of human reliability is often implemented for the identification of hazards through the What if? and HAZOP methods.

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