Lecture 14 «Drying process. Properties of wet air. Material balance of drying. Drying statics. Drying kinetics. Vacuum drying. Drying of gases. Dryers»

Aim: Formulate the properties of wet air. Explain the derivation of material balance of drying. Characterize drying statics, vacuum drying and drying of gases, dryers. Bring the derivation of the calculation formula for the drying kinetics.

Lecture summary: Drying is called the process of removing moisture from damp materials by evaporating it. Moisture can be removed from materials by mechanical ways (spinning, upholding, filtering, centrifugation). However, more complete dehydration is achieved by evaporation of moisture and evacuation of formed vapors, i.e. with the help of thermal drying.

By the method of supplying heat to the dried material, the following types of drying are distinguished:

1) convection drying – by direct contact of the dried material with a drying agent, which is usually heated air or flue gases;

2) contact drying – by transferring heat from the heat carrier to the material through the wall separating them;

3) radiation drying – by transferring heat by infrared rays;

4) dielectric drying – by heating in the field currents of high frequency;

5) freeze-drying - drying in a frozen state with a deep vacuum.

The last three types of drying are relatively rare and are called special types of drying.

The dried material under any drying method is in contact with wet gas (air), i.e. in the drying process, the main role belongs to drying agents. In industrial conditions, when convective drying as the heat carrier most air is used [1-3].

Main parameters of wet air

Air always contains some moisture. A mixture of dry air and water vapor is wet air. Wet air is characterized by the following basic parameters: absolute and relative humidity, moisture content and enthalpy (heat content).

Absolute humidity is the amount of water vapors contained in 1 m^3 of humid air (g/m^3, kg/m^3). Air with the maximum content of water vapor at a given temperature is called saturated. The amount of water vapor is determined by the temperature of the air.

Relative humidity or *degree of air saturation* φ is the ratio of the mass of water vapor $M_{w.v.}$, located in 1 m^3 of wet air, to the maximum mass of vapor $M_{m.v.v.}$ that can be contained in 1 m^3 of humid saturated air at a given temperature and pressure:

$$\varphi = \frac{\mathrm{M}_{w.v.}}{\mathrm{M}_{m.w.v.}} \cdot 100 = \frac{\rho_v}{\rho_s} \cdot 100\%, \tag{1}$$

where ρ_v – the vapor density, kg/m^3; $\rho_{s.v.}$ – density of saturated vapor, kg/m^3.

The vapor density is proportional to its partial pressure, therefore, the relative humidity can be expressed by the ratio of pressures

$$\varphi = \frac{p_v}{p_s}, \qquad (2)$$

where p_v – the partial pressure of water vapor corresponding to its density; p_s – the saturated vapor pressure at the same temperature.

If air is cooled, then its relative humidity increases. The temperature corresponding to the saturated state of vapor in air (φ = 100 %) at a given partial pressure is called the dew point ($t_{d.p.}$). When the air is cooled below the dew point, condensation of water vaporы occurs.

The amount of water vapor in humid air, referred to 1 *kg* of dry air, is called *the moisture content* (*kg*/*kg*):

$$x = \frac{G_{H_2O}}{G_{air}} = \frac{M_{H_2O}}{M_{air}} \cdot \frac{p}{P-p} \qquad (3)$$

Substituting in the last equation $p_v = \varphi p_s$ (from equation (2)), M_{H_2O} =18, M_{air} = 29, we obtain the dependence of the moisture content of air on its relative humidity

$$x = \frac{18}{29} \cdot \frac{\varphi p_s}{P - \varphi p_s} \qquad (4)$$

The enthalpy of humid air (I) refers to 1 *kg* of absolutely dry air and is determined at a given air temperature *t* (*°C*) as the sum of the enthalpies of absolutely dry air and water vapor:

$$I = \mathrm{c}_{d.a.} t + x i_v, \qquad (5)$$

where $c_{d.a.}$ – specific heat of dry air, J/kg·K; *t* – the air temperature, K; i_v – enthalpy of superheated vapor, J/kg.

The enthalpy of steam is determined by the empirical formula:

$$i_v = r_0 + c_v t = (2493 + 1{,}97) \cdot 10^3 \qquad (6)$$

where r_o = 2493·10^3 – constant coefficient, approximately equal to the enthalpy of vapor at 0 °C; c_v = 1,97·10^3 – specific heat of vapor, J/kg·К.

Representing the value i_v in expression (6) and accepting $c_{d.a.}$ = 1000 J/kg·K as a constant value, we find the enthalpy of humid air

$$I = (1000 + 1{,}97 \cdot 10^3 x)t + 2493 \cdot 10^3 x, \qquad (7)$$

where *x* – the moisture content, *kg*/*kg* of dry air.

Statics of drying

The statics of the process – the consideration of equilibrium data, on the basis of which the direction and possible limits of the process are determined.

Wet material gives moisture by evaporation into the environment. Environment – wet air. Therefore, the drying process will only take place if the vapor pressure of moisture at the surface of the dried material p_m is greater than the partial pressure of water vapor in air $p_{w.v.}$. That is, the condition for drying is the inequality $p_m > p_{w.v.}$. When $p_m = p_{w.v.}$ – the drying process stops. Each material can be dried only to an equilibrium moisture content (under atmospheric drying conditions).

The equilibrium humidity is determined by the property of the material to be dried, the nature of the connection with it of moisture and the parameters of the environment.

According to the theory of Academician P.A. Rebinder, there are three forms of the connection of moisture with the material: 1) chemical; 2) physico-chemical; 3) physico-mechanical.

A chemical bond is characterized by a strictly defined molecular ratio (hydrate or crystallization water).

The physicochemical connection of moisture with the material does not imply a strictly defined ratio (adsorption moisture, osmotic moisture, etc.). With the help of a physico-mechanical bond, water is held by the material in undefined proportions. The physico-mechanical form includes the structural bond, the capillary bond, and the wetting bond.

When drying, first free moisture is removed, then bound one. The boundary between free and bound moisture is called the critical moisture content of the material. The equilibrium humidity depends on the water vapor pressure, it is higher the more relative humidity of air.

Material balance of drying

If the wet material is supplied to the drying in an amount of G_1 *kg/s* with a humidity of u_1 parts by weight, after drying, G_2 *kg/s* of dried material with a moisture content of u_2 parts by weight is obtained and wherein the moisture W *kg/s* is evaporated, then the material balance is expressed by the equality:

for the whole quantity of substance

$$G_1 = G_2 + W \tag{8}$$

for absolutely dry substance:

$$G_1(1 - u_1) = G_2(1 - u_2) \tag{9}$$

From these equations, the amount of dried material G_2 and evaporated moisture W is determined.

For heat balance, it is necessary to know the air consumption for drying, which can be determined from the moisture balance.

The moisture balance can be expressed by equality

$$Lx_2 = Lx_0 + W, \tag{10}$$

from where the air flow is

$$L = \frac{W}{x_2 - x_0}, \tag{11}$$

where L – the amount of dry air, *kg*; x_o – moisture content of humid air at the inlet to the dryer, *kg/kg*; x_2 – moisture content of humid air at the dryer outlet, *kg/kg*; W – amount of moisture evaporated, *kg*.

Specific air consumption will be:

$$l = \frac{L}{W} = \frac{1}{x_2 - x_0} \tag{12}$$

It follows from expression (12) that the air flow will be the greater, the higher the initial moisture content x_o, which is determined by the temperature and relative humidity of the air. Other things being equal, the air flow will increase with increasing initial temperature and the initial relative humidity of the air. Consequently, the air consumption for drying in summer will be greater than in winter [1-3].

Kinetics of drying

Drying is a complex diffusion process, the speed of which is determined by the rate of diffusion of moisture from the depth of the material to be dried into the environment. The drying process is a combination of the processes of heat and mass transfer (moisture exchange) associated with each other.

By measuring the loss of the mass of the dried sample over time, it is possible to determine the change in moisture content u_a as a function of time τ. The dependence of absolute humidity on time is called the drying curve.

It follows from Fig. 1 that in the initial stage (section *AB*) the moisture content of the material decreases slowly and the heat is expended on heating the material from the initial temperature v_1 to the temperature of the wet thermometer $v = t_{w.t.}$. This is the heating stage of the material.

In the *BK* section, the moisture content of the material falls linearly, the drying is characterized by a constant velocity with a constant surface temperature of the material, $v = t_{w.t.}$.

Starting from point *K*, the drying proceeds along the curve *KC*. The temperature of the surface of the material then continuously increases and, once the equilibrium moisture reaches equilibrium, becomes equal to the heating air temperature $v = t_{air}$. Thus, the drying process is composed of a period of constant drying speed and a period of falling drying speed. The moisture content of the material at the point *K* is called the critical moisture content u_{cr}.

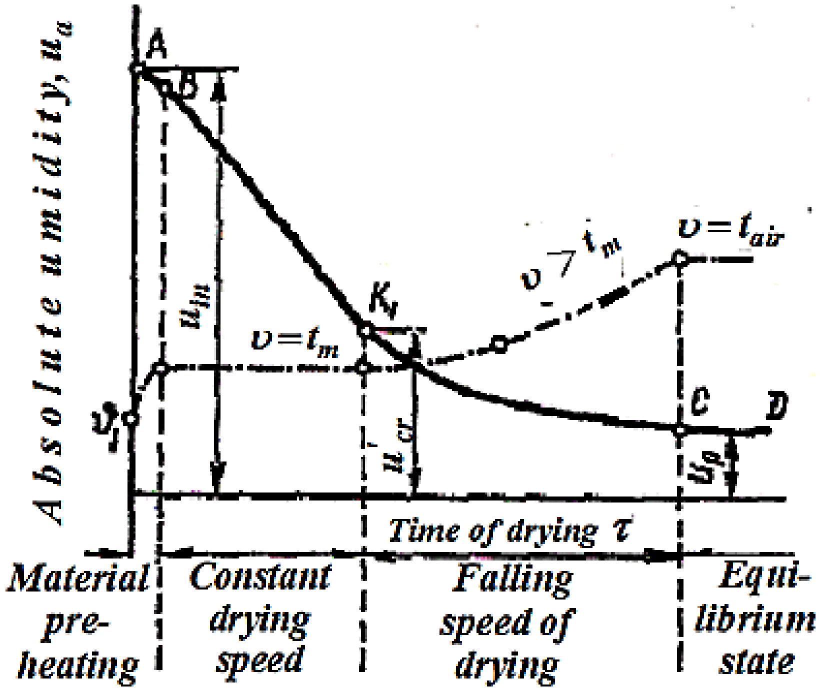

Fig. 1. Curve of drying the material and changing its temperature during the drying process: v – surface temperature of the material; v_1 – initial temperature of the material; $t_{w.t.}$ –the temperature of a wet thermometer; t_{air} – air temperature; u_{in} – initial umidity of the material; u_{cr} – the critical umidity of the material; u_{eq} – equilibrium umidity of the material

The drying rate is determined by external diffusion (diffusion of moisture vapor from the surface of the material to the environment), i.e. by temperature, humidity and rate of drying agent, but it does not depend on the moisture content of the material. The basic equation for the rate of evaporation is given in the following form:

$$\frac{du'}{d\tau} = \beta \Delta C F, \tag{13}$$

where ΔC – the difference in the vapor concentration at the evaporation surface and in the ambient air; F – the evaporation surface; β – the evaporation coefficient, taking into account the aerodynamic conditions of evaporation and the physical properties of the liquid.

The coefficient β can be determined by knowing the value of the Nusselt diffusion criterion

$$Nu' = \frac{\beta l}{D}, \tag{14}$$

where l – the length of the sample in the direction of air movement, *m*.

At forced motion of air to determine the diffusion Nusselt's criterion the dependence (15) is used,

$$Nu' = C \cdot Re^n (Pr')^m \tag{15}$$

The duration of a period of constant drying speed can be determined by the equation:

$$\tau = \frac{1}{K} \cdot \frac{u'_{in} - u'_{cr}}{u'_{cr} - u_{eq}}, \quad (16)$$

where K – the rate constant of the drying process (can be determined experimentally or through the mass emission coefficient to the gas phase); $u'_{in}, u'_{cr}, u_{eq} -$ initial, critical, equilibrium moisture content of the material.

The speed of the second drying period is determined by internal diffusion, depends on the moisture content and temperature of the material and is practically independent of the speed and humidity of the air. Set the drying time of the material exactly can only be experienced.

Vacuum drying

Removal of moisture from materials poorly enduring the effects of high temperatures is carried out at low temperatures. Therefore, for the purpose of intensification, the drying process is carried out under vacuum.

Advantages of vacuum drying are:

1) the driving force of the process increases, since with the pressure decrease in the dryer, the difference in vapor pressure of moisture over the material and in the environment increases;

2) complete removal of moisture is achieved;

3) valuable volatile solvents are captured;

4) the release of harmful gases and vapors from the dryer into the surrounding space is excluded;

5) due to the tightness of the system, contamination of the material is avoided.

Vacuum drying technique: the dried material is placed in a hermetically sealed chamber, from which air is pumped out with the air pump together with moisture vapor. The moisture vapor is detected in the capacitors. Capacitors are barometric or superficial. Inside the chamber, there are coils, or plates, through which hot water or steam is maintained at a constant temperature during drying. Under the influence of a temperature gradient, moisture diffusion occurs in the direction toward the evaporation surface and its steam generation. Vacuum drying is a thermal diffusion process.

The process of vacuum drying is a series of simultaneously proceeding complex processes – boiling, evaporation, condensation occurring in the pores and capillaries of a moist body, as well as an unsteady process of heat transfer, then the mathematical description of this process is very difficult.

Drying of gases

Removal of water vapors from gases is necessary when the multi-component gases are deeply cooled in order to separate them into fractions when transporting flammable gases through pipelines.

During transportation, even at normal temperature, the gas can produce complex compounds with water, while paraffinic hydrocarbons are precipitated as complex compounds with water. Therefore, natural gas must be dried to a temperature of -10 ^oC before transporting them.

Dehydration of gases is carried out by physicochemical (absorption, adsorption) and physical methods.

Absorption methods are based on the absorption of moisture from gases by liquid substances, whose aqueous solutions have a low water vapor pressure (glycerin, diethylene glycol 85 %).

Adsorption methods are based on the absorption of moisture from gases by solid substances – adsorbents. As adsorbents the solid $CaCl_2$, NaOH, KOH, bauxite, alumogel, silica gel, molecular sieves are applied.

Physical methods are based on cooling the drying gas in surface coolers with water or refrigerant, cooling after gas compression and sudden expansion of the compressed gas. The condensate which is then released from the gas is discharged through the separator.

Chamber dryer

Chamber dryers (fig. 2) represent tight chambers in which the dried-up material depending on his look settles down on grids, baking sheets, poles, clips and other devices. They are applied to drying of rather small amounts of material and at rather big duration of process.

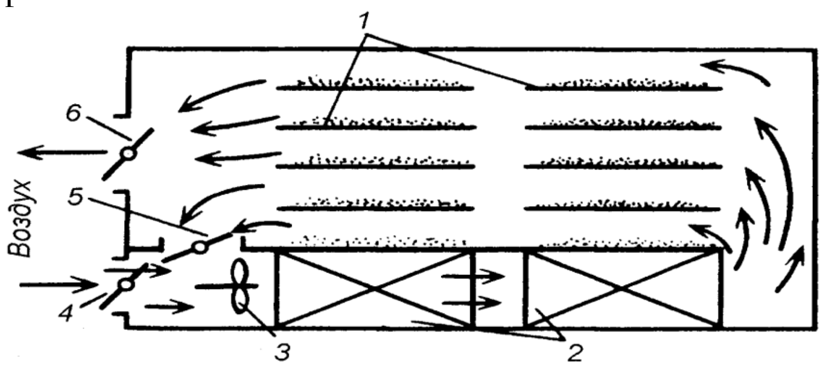

Fig. 2. Scheme of the chamber dryer:
1 – regiments for loading of the dried-up material; 2 – heater; 3 – fan; 4 – the gate for regulation of a consumption of fresh air; 5, 6 – gates (shiber) for regulation of expenses of the recirculating and fulfilled air

Chambers produce from a tree, a brick, concrete, metal and other materials which choice is caused by their sizes, temperature condition of process, and in some cases also properties of the dried-up material. The volume and the sizes of a chamber are defined by duration of drying and productivity of the device. For acceleration of loading and unloading of material baking sheets or grids for his laying place often on trolleys. Fresh air by means of the fan *3* through a heater *2* is given to space of a chamber in which there are regiments *1* with the dried-up material. Gates *5,6* serve for regulation of expenses of the recirculating and fulfilled air.

Questions to control:

1. What methods of thermal drying are used in industry?
2. What are the main parameters of the steam-air mixture? How are they determined from the $H - x$ diagram of the humid air state?
3. List and describe the types of connection of moisture with the material.
4. What is the form of recording the equations of material balance in terms of moisture in the material and in the drying agent?
5. What is the physical meaning of the specific consumption of the drying agent?
6. What type have the typical drying curves and drying speed of wet materials?
7. By what equation is the duration of the constant drying rate period calculated?
8. What is accepted as the driving force of the drying process and how is their average value determined?
9. List the advantages of vacuum drying.
10. What are the special ways of drying? What is the scope of their use?

Literature

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