Lecture №8. Material and heat balances of drying

Aim: Characterize the properties of humid air and the Ramzin $I - x$ diagram. Analyze the scheme for determining air parameters using the diagram $I - x$. Determination of air parameters using the diagram $I - x$. Determination of the driving force of the drying process on the diagram $I - x$. Draw and analyze the drying process in the theoretical and real dryer on the diagram $I - x$. Bring the equation of material and heat balances of drying.

Lecture summary: With any method of organizing the drying process, the wet material is in contact with a drying agent. Wet air, which is most often used as a drying agent, can be considered a binary mixture of dry air and water vapor. There are absolute and relative humidity and moisture content of air. Absolute humidity (ρ_v) is the mass of water vapor in a unit volume of humid air. Relative humidity (φ) is the ratio of the mass of water vapor in 1 m^3 at given temperature and total pressure to its maximum possible mass in 1 m^3 under the same conditions.

Since the vapor content can be characterized by partial pressure, the relative humidity of the air: $\varphi = \rho_v/\rho_{sat}$, where ρ_v is the partial pressure of water vapor in the air; ρ_{sat} - pressure of saturated steam at the same temperature. The moisture content of air (x) is the ratio of the mass of water vapor to the mass of absolutely dry air. The enthalpy of humid air refers to 1 kg of dry air and, according to the additivity rule, is defined as the sum of the enthalpy of absolutely dry air and the enthalpy of water vapor contained in one kilogram of dry air $I = I_{dry\ air} + xI_v$.

The basic properties of humid air with sufficient accuracy can be determined from the $I - x$ Ramzin diagram (Fig. 1).

Finding the position of a point on a diagram corresponding to a particular state of the vapor-air mixture requires knowledge of any pair of parameters t, φ, x, I (Fig. 2).

Upon contact with wet air, the material cannot be dried to a completely dry state. If the vapor pressure of the liquid in the material p_m differs from the partial pressure of the vapor in the gas flow p_v, then between the two phases there will be a mass exchange up to the equilibrium state, when $p_m = p_v$. The state of dynamic equilibrium corresponds to the limiting humidity of the material, which is called the equilibrium humidity u_{eq}.

In convective drying, the boundary layer of air near the surface of the wet material is saturated with water vapor and in the limit the partial pressure of water vapor will be p_{sat}. From the boundary layer, moisture diffuses into the surrounding air, since there is a pressure difference $\Delta p_v = p_{sat} - p_v$. This pressure difference Δp is the driving force of the drying process. At the inlet and outlet of the dryer, the differential pressure values Δp will be different.

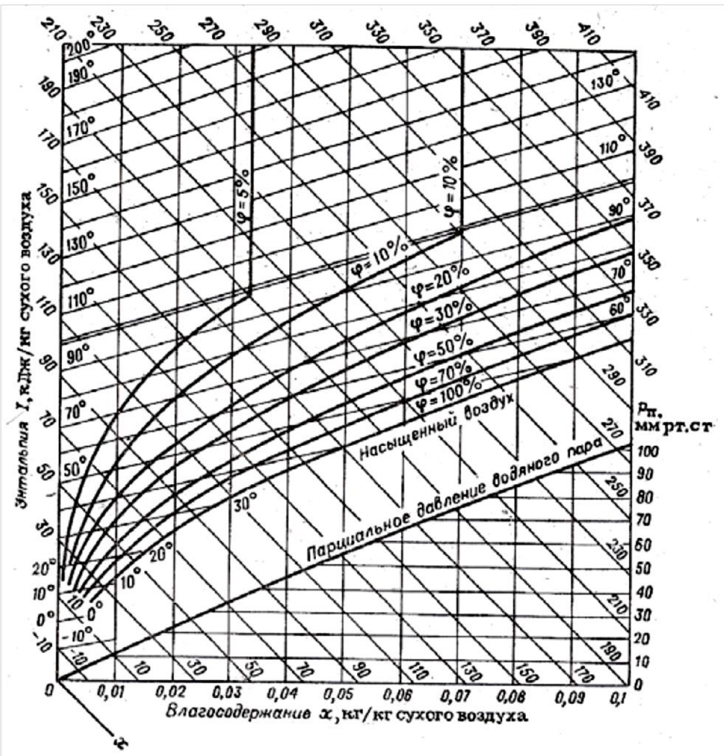

Fig. 1. $I - x$ diagram of humid air

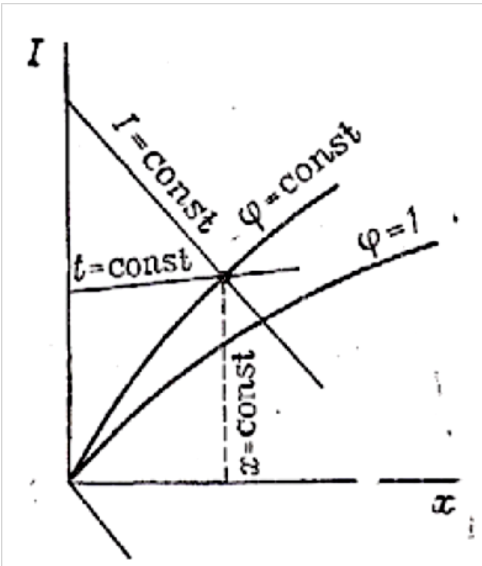

Fig. 2. Scheme for determining air parameters using the diagram $I - x$

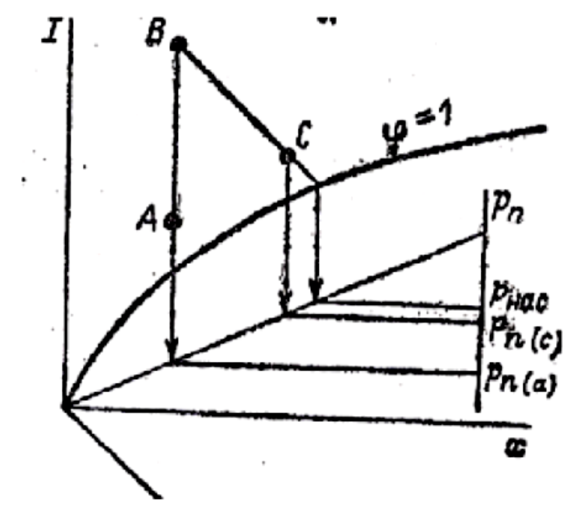

Fig. 3. Determination of the driving force of the drying process on the diagram $I - x$

To determine the average driving force of drying, we use the diagram $I - x$. In fig. 3, point A characterizes the atmospheric air, point B determines the characteristics of the air entering the dryer, and point C indicates the air leaving the dryer. The BC line characterizes the change in air properties during the drying process. Then the driving force at the air inlet to the dryer $\Delta p_1 = p_{sat} - p_{v\,(a)}$, at the outlet of the dryer $\Delta p_2 = p_{sat} - p_{v\,(c)}$ and the average driving force of the drying process

$$\Delta p_{av} = (\Delta p_1 - \Delta p_2) / [\ln\Delta p_1 / \Delta p_2]. \quad (1)$$

The moisture content of the material can be expressed as a percentage of either the total mass of the wet material u or the mass of the absolutely dry substance u'. The relation between them has the form $u = u'/(1 + u')$ or $u' = u/(1 - u)$.

The material balance of the flow is equal to the mass of the incoming material G_{in} the sum of the masses of the dried material G_{fin} and the moisture removed W

$$G_{in} = G_{fin} + W. \quad (2)$$

Another balance ratio corresponds to the equality of the mass of absolutely dry material at the inlet and outlet of the dryer

$$G_{in}\,(1 - u_{\mathrm{in}}) = G_{fin}\,(1 - u_{\mathrm{fin}}) = G_{dry}. \quad (3)$$

The amount of moisture removed from the material is proportional to the change in the moisture content of the material:

$$W = G_{in}\frac{u_{in}-u_{fin}}{1-u_{fin}} = G_{fin}\frac{u_{in}-u_{fin}}{1-u_{fin}} = G_{dry}\left(u'_{in} - u'_{fin}\right). \quad (4)$$

This moisture in the drying process in the form of vapor enters the air, the moisture content of which increases. The balance of drying moisture is

$$Lx_0 + W = Lx_2. \quad (5)$$

where L – the flow rate of dry air, kg/s; x_0 – moisture content of atmospheric air, kg/kg; x_2 – moisture content of the spent drying agent, kg/kg.

The consumption of absolutely dry air required for drying will be

$$L = W/(x_2 - x_1). \quad (6)$$

The specific air flow rate per unit mass of moisture removed from the material is equal to

$$l = L/W = l/(\,x_2 - x_1). \quad (7)$$

Atmospheric air before the dryer is heated in the air heater, where heat Q is supplied to it, for example, from heating steam

$$Q = L\,(I_1 - I_0), \quad (8)$$

where I_0, I_1 – specific enthalpies of air at the entrance to the heater and at the exit from it, kJ/kg of dry air.

Consider the image of the drying process in a theoretical dryer on the diagram $I - x$ (Fig. 4). To determine the position of point A, which characterizes the state of atmospheric air, two any of its parameters should be known, for example, t_0 and φ_0. By the intersection of the lines t_0 = const and φ_0 = const, we find point A and determine the moisture content x_0 and the enthalpy I_0 of atmospheric air.

When air is heated to the temperature t_1 in the air heater, its moisture content does not change ($x_0 = x_1$), but its relative humidity (φ_1) sharply decreases.

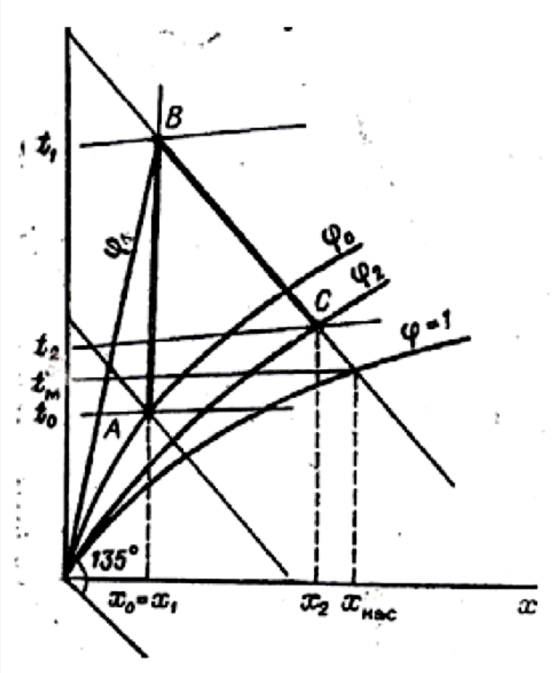

Fig. 4. Process image in theoretical drier on the diagram $I - x$

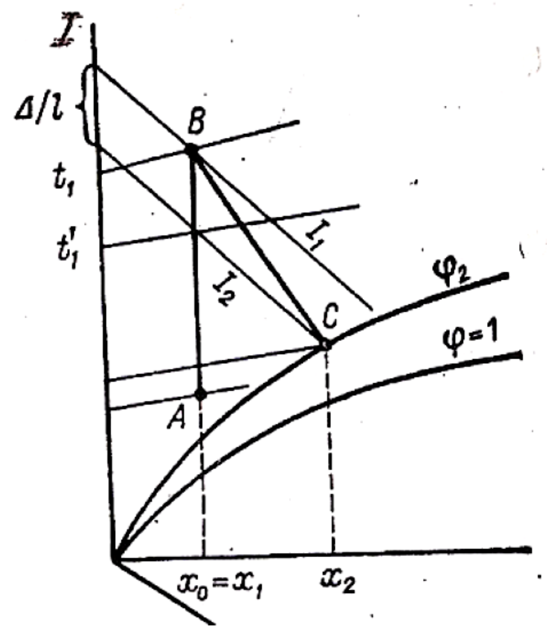

Fig. 5. Normal drying option in a real dryer in diagram $I - x$

From point A, we draw a vertical to the intersection with the isotherm t_1 = const and determine the position of point B, which characterizes the state of heated air before entering the drying chamber. The segment AB reflects the process of heating the air in the heater at $x_0 = x_1$ = const. From point B, we draw the line I_1 = const to the intersection with the isotherm t_2 = const and we obtain point C, which characterizes the state of exhaust air at the outlet of the dryer. The segment BC reflects the process of cooling the air during the drying process. In a theoretical dryer, $I_1 = I_2$ = const, since the amount of heat given off by air to evaporation of moisture fully returns to it with this evaporated moisture.

Let's make the equation of heat balance of convective drying. We introduce the following additional notations: Q_{loss} – heat loss to the environment, W; t_{in} and t_{out} – material temperatures at the inlet and outlet of the dryer, $^{\text{o}}$C; c_{mat} and c_{moist} – specific heat capacities of the dried material and moisture, respectively, J/(kg·K).

We consider the mass of the initial wet material in the heat balance as the sum of the masses of the dried material and evaporated moisture

$$G_{in}c_{mat}t_{in} = G_{fin}c_{moist}t_{in} + Wc_{moist}t_{in}. \quad (9)$$

In drawing up the heat balance, it is necessary to take into account that there may be transport devices in the dryer on which the material to be dried is placed. The mass of these devices is G_{tr}, kg/s; the specific heat capacity of the material from which they are made c_{tr}, J/(kg·K); $t_{t.in}$ and $t_{t.fin}$ – material temperatures at the inlet and outlet of the dryer, ^{o}C.

The equation of the heat balance of the drying process, in which all the quantities of heat entering the plant are equal to all the quantities of heat leaving it, has the form

$$Q + LI_0 + G_{in}c_{mat}t_{in} + Wc_{moist}t_{in} + G_{tr}c_{tr}t_{t.in} = LI_2 + G_{fin}c_{moist}t_{fin} + G_{tr}c_{tr}t_{t.fin} + Q_{loss} \quad (10)$$

Solve this equation for the amount of heat received by the air in the air heater

$$Q = L(I_2 – I_0) + G_{fin}c_{moist}(t_{fin} – t_{in}) + G_{tr}c_{tr}(t_{t.fin} – t_{t.in}) – Wc_{moist}t_{in} + Q_{loss}. \quad (11)$$

Dividing all terms of the balance equation by W, we get

$$q = l(I_2 – I_0) + q_m + q_{tr} – c_{moist}t_{in} + q_{loss}, \quad (12)$$

where $l(I_2 – I_0)$ – the specific heat consumption in the air leaving the dryer; q_m – specific heat consumption for heating the material; q_{tr} – specific heat consumption for heating vehicles; q_{loss} – specific heat loss to the environment.

Denoting the last four terms of the equation by the symbol $\Delta = q_m + q_{tr} – c_{moist}t_{in} + q_{loss}$, we obtain the equation of the heat balance of the real dryer

$$q = l(I_1 – I_0) = l(I_2 – I_0) + \Delta. \quad (13)$$

When $\Delta = 0$, the enthalpy $I_1 = I_2$, and such a dryer is called theoretical. The drying process in it proceeds adiabatically with constant enthalpy, since the moisture evaporated from the material introduces the same amount of heat into the air, which it gives, when cooled, to evaporation of moisture. For a theoretical dryer, the specific heat consumption is $q_{theor} = l(I_1 – I_0) / (x_2 – x_0)$.

The difference in specific heat consumption in real and theoretical dryers will be $q – q_{theor} = (I_1 – I_2) / (x_2 – x_0) = \Delta$.

The value $\Delta < 0$, when the enthalpy $I_2 > I_1$increases, corresponds to the drying variant with an additional heat supply (q_{add}), which exceeds the heating losses of the material, transport devices and losses from the surface of the dryer to the environment. The value $\Delta > 0$ corresponds to a decrease in the enthalpy of the drying agent $I_2 < I_1$. The enthalpy equation for a real dryer has the form $I_1 = I_2 + \Delta/l$. Thus, the construction of the process in a real dryer is reduced to the determination of the slope of the drying line BC. This line may deviate in one direction or another from the line I_2 = const , depending on the sign of the value Δ (Fig. 5).

When $\Delta > 0$, the exhaust air enthalpy decreases ($I_1 > I_2$). In this case, to build a drying line from the intersection point of the lines x_0 = const and I_2 = const, we postpone up (on the scale of axis l) the segment Δ/l and find the position of point B, which characterizes the properties of air entering the dryer. Thus, the segment BC reflects the process of real drying.

When $\Delta < 0$, the enthalpy $I_1 < I_2$ as a result of the additional heat supply $\Delta = (q_m + q_{tr} + q_{loss}) - (c_{moist}t_{in} + q_{add})$. The construction of the BC line is carried out similarly to that considered in Fig. 8, only the segment Δ/l is laid down from the intersection point of the lines x_0 = const and I_2 = const.

Questions to control:

1. Describe the properties of wet air and the Ramzin diagram $I - x$.
2. Analyze the scheme for determining air parameters using the diagram $I - x$.
3. Determine the air parameters using the diagram $I - x$.
4. Determine the driving force of the drying process in diagram $I - x$.
5. Draw and analyze the drying process in a theoretical dryer in diagram $I - x$.
6. Draw and analyze the drying process in a real dryer in diagram $I - x$.
7. Give the equation of material balance of drying.
8. Give the equation of heat balance of drying.

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