14 Drying
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I Basic relations and definitions

Drying is a process which is used for removing the liquid from the solid material. In standard chemical engineering practice drying of the water (compound A) from the solid (compound C) by evaporating to the flow of overheated air (compound B) is the most common practical example. It is relatively complex process combining the heat and the mass transport. In our laboratory dryer the heat transport which is necessary for the evaporation of the water, is realized only by the heat convection from the air to the drying material.

From mass transport point of view, one must understand the drying as a diffusion process. During first period of drying, water which is contained in material evaporates from the material surface to the air flow (by external diffusion). After formation the moisture gradient inside the material second drying period begins. During this period water is transported inside material to the surface (internal diffusion). Rate of the slower process determines overall drying rate.

Wet material can be described as a binary mixture of the absolutely dry solid material and the water (moisture). Concentration of water can be expressed by relative mass fraction of the liquid

\[ X_A = \frac{m_A}{m_C}, \quad (14-1) \]

where \( m_A \) is the mass of water and \( m_C \) is the mass of dry material. Particulate solid used in our laboratory is non-porous, i.e. for water evaporation from saturated material it is necessary to add energy equal only to vaporization heat of the water. The moisture can be free (which can be removed) or bounded (equilibrated) which can not be removed even in infinite time. Equilibrium moisture content depends on air and drying material properties.

The air moisture can be expressed by relative mass fraction in the gas

\[ Y_A = \frac{m_A}{m_B}, \quad (14-2) \]

where \( m_A \) is the mass of water vapors and \( m_B \) is the mass of dry air. Another possible expression of the air moisture is by relative moisture in form

\[ \varphi = \frac{p_A}{p_A^0} \quad (14-3) \]

where \( p_A \) is partial water pressure in air and \( p_A^0 \) is vapor pressure at given temperature.

Mass and heat transport proceed together during drying. Description of these processes is based on description of the process determining overall process rate (the slowest process). In case of drying the limiting step is the mass transfer. The mass transfer driving force (which is equal to the concentration gradient) can be therefore used for description of drying. The drying rate expressed as an intensity of the mass flow can be defined as

\[ \phi_A = \frac{d^2 m_A}{dA d\tau} \quad (14-4) \]
It is generally spatiotemporal function of the dryer and depends on drying conditions. Drying rate can also be described by gas-phase mass transport equation in form
\[
\phi_A = k_Y (Y_{Aw} - Y_A),
\] (14-5)
where \(k_Y\) is the mass transfer coefficient based on driving force defined by relative mass fraction of the moisture in air, \(Y_A\) represents the average moisture in air and \(Y_{Aw}\) is the moisture content on the boundary between air and saturated material. Another possible definition of the drying rate should be using partial pressure of the vapors in air
\[
\phi_A = k_p (p_{Aw} - p_A).\] (14-6)

Changes in the dew point temperature \(t_r\) and in variables \(Y_A\) and \(p_A\) can be neglected in our laboratory dryer, i.e. these variables can be assumed spatially constant in dryer.

Let’s assume that at the beginning of drying particles of the solid material are fully saturated by thin water layer. Initial moisture content is \(X_{Ap}\) and initial temperature of saturated material is \(t_p\). In time \(\tau = 0\) saturated material with initial conditions \((X_{Ap}, t_p)\) is connected with the air flow with parameters \((t > t_p, Y < Y_{Aw})\). The drying then begins. Dependence of the moisture content on time is qualitatively shown in Fig.14-1.

Overall drying process can be divided in three parts:

1. **Warm-up period**

   Material starts to be heated from initial temperature \(t_p\) to the wet bulb temperature. Moisture starts to evaporate from the surface. Mass and heat transfer driving forces are non-zero. Concentration of water decreases. Process is running on drying curve \([X_A = X_A(\tau)]\) from point A to point B. Drying of water from the surface slows down heating of the material because the heat from the air is consumed by the evaporation. Warm-up period should be relatively short and sometimes can be even non-catchable.

2. **First drying period (constant-rate period of drying)**

   This period begins at point B in Fig. 14-1. At this point temperature of the material is equal to the wet thermometer temperature and stays constant, i.e. the added heat is consumed by evaporation of the free water. Driving force in Eq. (14-5) and drying rate \(\phi_A\) are constant. Vapor pressure on the material surface during constant-rate period is equal to vapor pressure of water on the clean water in the same temperature \(t_w\). In point C moisture content is equal to the critical moisture content \(X_{Ac}\). During constant-rate period the drying rate depends on temperature, moisture content and mass flow of air. The drying rate is not function of bed depth and actual moisture content.

3. **Second drying period (falling-rate period)**

   In point C water starts to percolate, i.e. the surface of the material dries up and the first particles are connected with the air. The drying rate starts to decrease. Temperature of the material is rising – point D, and causes decreasing of the mass and heat transfer driving forces. The path of evaporated vapors is more complex, i.e. the resistance again the diffusion is bigger. In point E material temperature is nearly equal to air temperature and moisture content is equal to the equilibrium moisture content \(X'_{A}\). The mass and heat transfer stop at this point, \(\phi_A \rightarrow 0\), and it is impossible under actual conditions to dry material more. Theoretically, achieving the equilibrium state takes infinitely long time.
Fig. 14-1 Qualitative dependence of moisture content $X_A$ and temperature $t$ on drying time.

In laboratory practice drying kinetics during first drying period will be measured. During this period the material surface is isothermal with temperature equals to the wet thermometer temperature. Due to temperature and moisture changes are small in laboratory dryer, their values can be assumed spatially constant. The drying rate is therefore spatially independent. During first drying period the drying rate is not function of time as well. Eq. (14-4) can be then simplified as

$$\phi_A = \frac{m_A}{A \tau} = \frac{\dot{m}_A}{A},$$

where $m_A$ is the mass evaporated from the material surface with area $A$ during time $\tau$ and $\dot{m}_A$ is the mass flow of evaporated water.

The drying rate in laboratory dryer can be calculated from the moisture content as follows:
\[ \dot{m}_A = -m_c \frac{dX_A}{d\tau} \]  

(14-8)

using Eq. (14-7) the drying rate can be rewritten as

\[ \phi_A = -\frac{m_c}{A} \frac{dX_A}{d\tau} \]  

(14-9)

From this Eq. can be seen that if \( \phi_A \) is constant then \( \frac{dX_A}{d\tau} \) must be constant as well.

For evaporating of water it is necessary to add a heat. The heat flow from air can be expressed be the heat transfer equation:

\[ \dot{Q} = \alpha (t_1 - t_w) A, \]  

(14-10)

where \( t_1 \) is temperature inside the dryer and \( t_w \) is temperature on the material surface. The heat transfer coefficient \( \alpha \) is constant on whole area \( A \). The heat flow can be described by enthalpy balance equation. The temperature difference of air inside the laboratory dryer can be neglected, i.e. it can not be used for the heat flow calculation. During first drying period the heat added by convection to the drying material is fully consumed by the moisture evaporation

\[ \dot{Q} = \Delta h_{vl,\lambda} \dot{m}_A \]  

(14-11)

where \( \Delta h_{vl,\lambda} \) represents latent heat of vaporization at wet thermometer temperature \( t_w \). Combining Eqs. (14-7), (14-10) a (14-11) the heat transfer coefficient is

\[ \alpha = \frac{\Delta h_{vl,\lambda}\phi_A}{t_1 - t_w} \]  

(14-12)

The drying curve – dependence \( X_A = X_A(\tau) \) – for chosen material and drying conditions can be obtained only experimentally. Another common form of the drying curve is described as dependence of the drying velocity on the moisture content, \( \phi_A = \phi_A(X_A) \). Typical drying curves are shown in Fig. 14-2.

Here three drying periods can be easily distinguished – warming-up, constant- and falling-rates of drying.

Due to similarity between the heat and mass transfer it is possible to find correlations between heat and mass transfer coefficients. For the moist air can be found in very simple form

\[ \alpha / k_Y = C_{pg} \]  

(14-13)

where \( k_Y \) and \( \alpha \) are the mass and heat transfer coefficients appearing in Eq. (14-5) and (14-12), \( C_{pg} \) is the specific heat of the moist air per 1 kg of absolutely dry air.

From two known parameters of the moist air one can find corresponding point in enthalpy diagram and determined all the other parameters. Students also can use computer subroutine „vlvzduch“(which is installed on computers in student laboratory based on definitions and equations described earlier). Using this software is faster and easier than the reading from the enthalpy diagram.
The specific consumption of air defined as the mass of the absolutely dry air which is necessary for evaporation of 1 kg of water, is another important characteristic. During first drying period can be determined as

\[ l = \frac{m_{Bl}}{m_{Al}}, \tag{14-14} \]

where \( m_{Al} \) is the mass of water evaporated from material during first drying period, \( m_{Bl} \) is the consumption of dry air during the same period and \( l \) represents the specific enthalpy per 1 kg of dry air.

Value \( m_{Bl} \) is calculated from Eq. (14-20) and \( m_{Al} \) is determined from

\[ m_{Al} = A \phi \alpha \eta. \tag{14-15} \]

The heat efficiency \( \eta \) during first drying period can be defined as ratio of heat \( Q_I \) consumed by water evaporation (at wet thermometer temperature) to the heat supplied by the electric heating

\[ Q_I = \Delta h_{IW,A} m_{Al} \tag{14-16} \]

\[ Q_T = (l_I - l_0)m_{Bl} \tag{14-17} \]

\[ \eta = \frac{Q_I}{Q_T} \tag{14-18} \]

where \( l_I \) is the specific enthalpy of air after the air heater (warm-air furnace), \( l_0 \) is the specific enthalpy of air before the air heater and \( m_{Bl} \) is the mass of air consumed during first drying period. The specific enthalpy of air can be obtained also from computer routine „vlvzduch“, see Tab.1 in paragraph VI.2 for details. Compare the added heat \( Q_T \) calculated using „vlvzduch“ with the reading from the electrometer. The calculated heat will be smaller due the loses in feed pipeline.
Fig. 14-3 Schematic figure of the laboratory dryer

1a - 1c ventilators
2 thermometer of the incoming air
3 flowmeter
4 rotational speed sensor of flowmeter turbine
5 electrical heating
6 connecting thermally isolated pipeline
7 additional firing
8 thermometer of the heated air
9 lid of the dryer
10 dryer
11 drying hurdle
12 scale
13 sensor of moisture meter
14 outcoming pipeline

Fig.14-4 Schematics of the measuring panel

1. temperature before the calorifier \( t_0 \), °C
2. temperature after the calorifier \( t_1 \), °C
3. consumed energy, Wh
4. dew point \( t_r \), °C
5. evaluation unit and flowmeter display
6. power switch
7. ventilator switch
8. switch of the heating
9. rotational speed controller
II Objectives

1. Evaluate and plot graphically measured data in form of drying curve, i.e. dependence $X_A = X_A(\tau)$. Find critical moisture content and time of the first drying period.
2. Evaluate and plot graphically measured data in form of dependence of the drying velocity on moisture content.
3. Calculate and compare the heat and mass transfer coefficients.
4. Determine the heat efficiency of the dryer during first during period.
5. Calculate the specific consumption of the air during first drying period.

III Plant description

Schematic figure of the laboratory dryer is shown in Fig. 14-3. The dryer consists of three axial ventilators $1a, 1b, 1c$ connected in series (for increasing of transport height). Resistance thermomether $2$ for measuring temperature of the incoming air $t_0$ (on measuring panel is called temperature before the calorifer) is installed after the ventilators. Equipment in rustless envelope is turbine flowmeter $3$ with rotational speed sensor $4$. The volume flow of air is measured at barometric pressure and temperature $t_0$. Digital barometer for reading of barometric pressure can be found on the wall near the laboratory entrance door. The over-heated air runs through electric calorifer $5$ and thermally isolated dural tube $6$ to the dryer. Parts numbered $1$ to $5$ are located in the shelf beyond the dryer. The dryer $10$ with mechanical scale $12$ is lying on the table under the shelf. Drying hurdle with drying material $11$ can be found on scale and can be inserted from the top to the dryer by opening the lid with organic glass $9$. Dew point temperature sensor $13$ is located in the dryer. The additional firing $7$ for compensation of heat loses in interconnector $6$ is situated before the dryer, followed by thermometer $8$ connected with the additional firing controller. Thermometer $8$ shows input temperature to the dryer $t_1$ (on the measuring panel is called temperature after the calorifer or temperature inside the dryer). Air flows out from the dryer by exhaust pipe $14$.

Schematic figure of the measuring panel with description of all important parts is shown in Fig. 14-4. Rotational speed controller $9$ is for setting of the wanted air flow. Ventilators are switched on by switch $7$. Before measurement it is necessary to switch on power supply switch $6$. Parts of the dryer which are not labeled on the measuring panel are not used at the moment.
IV Work description

IV.1 Heating of the dryer

Switch on power supply switch 6. Read the barometric pressure. Set the controller 9 to zero value, switch on ventilators, set needed air flow and switch on the heating. Wait 10 minutes for condition stabilizing. Each 5 minutes write temperature inside the dryer. Heating is finished when temperature difference after three following readings is smaller than 1.5 °C. Value of the air flow can not fluctuate more than ±1m³h⁻¹.

IV.2 Preparations

Prepare specified mass of the solid material and specified volume of the distilled water. Scale the biker with water and add the drying hurdle to the dryer. Saturate dry material by the water and then rescale the biker. Difference between these two readings determines real amount of the added water (write the amount to the protocol and use it for calculations) It is necessary to prepare saturated material just before the measurement of the drying begins. Otherwise the water can vaporized under undefined conditions.

IV.3 Measurement

During measurement of drying every 10 minutes write all values wanted in your laboratory protocol. Due to air flow the scale reading usually fluctuates with error ±2 g. Stop the measurement when the mass loss of drying hurdle is smaller than 1g per 10 minutes. After finishing the measurement switch of the heating and wait until the temperature in the output from the calorifer falls to 40°C. Then switch of the ventilator and equipments.

V Safety instructions

1. Ventilator can be switched on only when the rotational speed controller is in position 0.
2. Using another buttons than buttons marked by numbers 2 and 4 in Fig. 14-4 is strictly prohibited.

VI Experimental data processing

VI.1 Determining of the dependence of the drying velocity on the moisture content

First, evaluate dependence of the moisture content on drying time (𝑋ₐ = 𝑋ₐ(𝜏)), see Fig. 14-5. Calculate values of moisture content 𝑋ₐ from Eq. (14-1). Drying rate during constant-rate period (first drying period) corresponds to multiple value of the direction of the linear part of the function 𝑋ₐ(𝜏), see Eq. (14-9). Before determining the direction it is necessary to find linear part of the dependence. One can eliminate points in curved part visually but more exact way is to determine the direction after elimination of each point by least square method.
VI.2 Determining of the mass and heat transport coefficients during first drying period

Mark the boundaries (the beginning and the end) of first drying period in laboratory protocol. (Notice, time of the warming-up period \( t_0 \) can not be sometimes neglected and then it is necessary to take off it from overall drying time). Calculate average needed values for first drying period \((t_0, t_1, \text{and } t_r)\). From Eqs. (14-5) and (14-6) calculate the mass transfer coefficients. From Eq. (14-12) calculate the heat transfer coefficient and verify the truth of Eq. (14-13). Brief manual for determining needed parameters of the saturated air using the computer subroutine "vlvzduch" is shown in Tab. 1.
Table 1 Brief manual for the use of the computer subroutine “vlvzduch”

<table>
<thead>
<tr>
<th>State of the air – input data for subroutine</th>
<th>Number of data combination in subroutine</th>
<th>Wanted (output) values - symbol in text and name in subroutine</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry thermometer temperature $t_0$</td>
<td>2</td>
<td>$l_0$ Enthalpy</td>
</tr>
</tbody>
</table>
| dew point temperature $t_r$                 |                                        | $
u$ Specific volume                             |
|                                           |                                        |                                                  |
| dry thermometer temperature $t_1$          | 2                                      | $l_1$ Enthalpy                                    |
| dew point temperature $t_r$                 |                                        | $t_w$ Dew point temperature                      |
|                                           |                                        | $Y_A$ Relative mass fraction of water             |
|                                           |                                        | $p_A$ Partial pressure of water vapor             |
| Saturated air in temperature $t_w$         | 1                                      | $Y_Aw$ Relative mass fraction of water            |
| dry thermometer temperature $t_w$          |                                        | $p_Aw$ Partial pressure of water vapor            |
| wet thermometer temperature $t_w^*$         |                                        |                                                  |

For saturated air dry and wet thermometer temperatures are the same.

Value of $C_{pg}$ can be calculated from

$$C_{pg} = Y_A C_{pA} + C_{pB},$$  \hspace{1cm} (14-19)

where $C_{pA}$, $C_{pB}$ are the specific heat capacities of water vapor and dry air and can be found in chemical engineering tables at temperature $t_1$.

VI.3 The heat efficiency of the dryer and the specific air consumption during constant-rate period of drying calculations

The heat efficiency can be calculated from Eq. (14-18). The latent evaporation rate at temperature $t_w$ can be found in chemical engineering tables. The specific air consumption can be obtained from Eq. (14-14). Use value of the specific volume of the saturated air $\nu$ (obtained form subroutine „vlvzduch“) for calculation of the mass of the dry air consumed during first drying period $m_{BI}$. Then

$$m_{BI} = V \tau_I / [\nu(1 + Y_A)],$$  \hspace{1cm} (14-20)

where $V$ is volume flow of the saturated air (read the value on the flowmeter) and $\tau_I$ is time during first drying period.

Compare the amount of heat added during first drying period $Q_I$ calculated from Eq. (14-16) with the value of the consumed electric energy measured on the electrometer after the same time.

VII List of symbols

$A$ area of the drying hurdle $\hspace{1cm}$ $m^2$

$C_{pg}$ specific heat capacity of the moist air per 1 kg of dry air $\hspace{1cm}$ $J \cdot kg^{-1} \cdot K^{-1}$

$h$ specific enthalpy $\hspace{1cm}$ $J \cdot kg^{-1}$

$\Delta h_{li}$ latent heat of evaporation $\hspace{1cm}$ $J \cdot kg^{-1}$

$l$ specific enthalpy of the wetted air per 1 kg of dry air $\hspace{1cm}$ $J \cdot kg^{-1}$
\( k_p \) mass transfer coefficient defined in Eq. (14-6) \( \text{kg m}^{-2}\text{s}^{-1}\text{Pa}^{-1} \)

\( k_Y \) mass transfer coefficient defined in Eq. (14-5) \( \text{kg m}^{-2}\text{s}^{-1} \)

\( l \) specific consumption of air

\( p_A^0 \) vapor pressure of water vapors \( \text{Pa} \)

\( \nu \) specific volume of the moist air \( \text{m}^3\text{kg}^{-1} \)

\( \dot{V} \) volume flow of the moist air \( \text{m}^3\text{s}^{-1} \)

\( X_A \) relative mass fraction of water in dried material

\( Y_A \) relative mass fraction of water in air

\( \phi \) drying velocity \( \text{kg m}^{-2}\text{s}^{-1} \)

\( \varphi \) relative moisture of air

\( \tau_0 \) time of the warming-up period \( \text{s} \)

\( \tau_1 \) time of the first drying period \( \text{s} \)

\( \eta \) heat efficiency of the dryer

Subscripts

- \( A \) water in material
- \( B \) absolutely dry air
- \( C \) dry material
- \( c \) critical value
- \( p \) initial value
- \( T \) heating (calorifer)
- \( w \) surface of material (corresponds to wet thermometer temperature)
- \( I \) first drying period

VIII Questions

1. What are external and internal diffusion?
2. What types of dryer do you know?
3. How is the air flow measured?
4. Discuss achieved value of the heat efficiency. Is it possible to increase it by changes in our laboratory dryer or by construction changes?
5. How can be state of the air (moisture content, enthalpy etc.) determined in our laboratory?
6. Describe the principle of determining of critical moisture content from measured data set.
7. Is it possible to measure experimentally moisture content in air?