

THERMODYNAMIC ASPECTS OF DRYING PROCESS

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ABSTRACT

By using a thermodynamical balance of a fluidized bed dryer the following energy consumption not recorded in heat calculations by now have been explained:

- for the creation of particles fluidization, and
- for extension of vapors separated during the drying of material.

These costs decrease the temperature of the drying agent entering the working chamber and deteriorate the efficiency of utilization of its temperature potential.

The not-recording of these energy consumption leads to inconsistency of energy calculations of the process made in air cooling and in evaporated water quantity.

During the experimental investigation of the drying process of wet materials in fluidized bed, (drying of wet-separated sesame and sun-flower seeds; high-moisture content crystal materials as sugar, sea-salt etc.) even at a stationary mode of operation, there is a frequent discrepancy between energy consumption according to the cooling of drying agent during its passing through the material bed (Q_L) and according to the quantity of evaporated water (Q_W). This discrepancy considerably surpasses the possible energy losses as a result of the heat-exchange with the environment and is due to unrecorded energy consumption in the balance.

The methodology accepted by several authors concerning drying process calculation (Elenkov, 1987, 1995; Ginzburg, 1985; Pakowski, 1987) records means of the s.c. correction for a real drying process Δ the energy consumption for heating the material q_m and the transport device q_r to the temperature at which they leave the drying chamber, as well as the losses due to heat-exchange with the environment q_{env} referred to a unit weight of evaporated water.

$$\Delta = q_{add} + c_w \theta_1 - \sum q_{los}, \quad (1)$$

where: $\sum q_{los} = q_{tr} + q_m + q_{env}$;

θ_l is the initial temperature of the material, $^{\circ}\text{C}$;

c_w is the specific heat capacity of the water, $\text{J}/(\text{kg}\cdot\text{K})$.

In (Ginzburg, 1985) the existence of a one more type of energy consumption in the drying process that are the result of a non-isobar change of dry gas state - q_{th} has been proved.

In order to reveal new, non-recorded by now energy losses during drying and especially during fluidized bed drying, and its modifications, it is purposeful to make a thermodynamic analysis of the wet gas state change when it passes through the drying chamber /1/ between two cross-sections - B - B - immediately before the gas-distributor /3/, and - C - C - after leaving the fluidized bed (Fig. 1). These are the cross-sections where the input and output drying agent temperature is measured and between which the process of moisture evaporation from the wet substance is implemented.

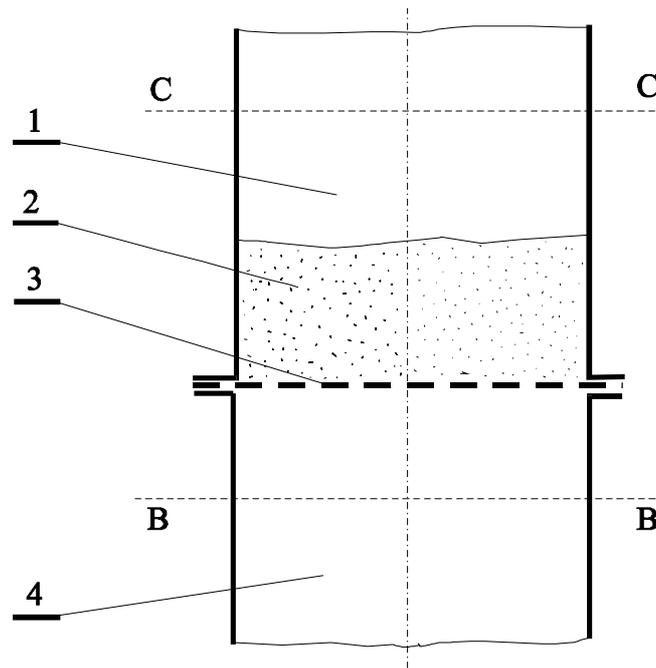


Fig. 1

Conditionally the process of wet gas change can be divided into four processes some of which flow out at one and the same time, as follows:

a) Adiabatic expansion into the gas-distributor /3/. The high velocities of the gas stream and the small linear dimension of the gas-distributors in the direction of the flow practically exclude exchange with outer sources. The work of friction dl_{fr} is transformed into an equivalent quantity of heat dq_{fr} that is not reflected on the gas enthalpy value. The low expansion degrees in the gas-distributor, as well as the drying agent pressures near the atmospheric one that are utilized in drying technique allow the wet gas to be looked upon as ideal gas, with accuracy sufficient for the engineering practice. At these conditions according to the first law of thermodynamics, the technical work done by the gas in its adiabatic expansion and its enthalpy change can be determined after the equation:

$$\Delta i_s = -l_t = \int v \cdot dp = \int R_v T \frac{dp}{p} = R_v T \ln \frac{p_2}{p_1} = R_v T \ln \left(1 - \frac{\Delta p}{p_1} \right) \quad (2)$$

Because $\Delta p \ll p$ and for small argument values the function $\ln x \approx (1 - x)$ it follows that:

$$\Delta i_s = -l_t = R_v T \frac{\Delta p}{p_1} = \frac{\Delta p}{\rho_1} \quad (3)$$

b) Quasiisothermal expansion of the wet gas during its passing through the fluidized - bed. The intensive bed scrambling, the mass - exchange, the considerable difference in the gas heat capacities and the material forming the bed, practically create an isothermal field in the fluidized - beds. The s. c. “active” zone is an exception - the zone that is in direct contact with the gas - distributor, within which the gas is intensively cooled down from the temperature it has when it enters the drying chamber to the bed the gas expands isothermally, at a temperature practically equal to the average surface temperature of the particles forming the bed.

From the ideal gas thermodynamic it is known that the enthalpy change in a isothermal process $\Delta i_t=0$, while a technical expansion work is done on account of an equivalent quantity of input heat to the equality :

$$q_t = l_{t,t} = R_v T \cdot \ln \frac{\Delta p}{p}, \text{ that at } \Delta p \ll p \text{ is transformed into:}$$

$$q_t = l_{t,t} = \frac{\Delta p}{\rho}. \quad (4)$$

c) Isobaric wet gas cooling down to average bed temperature. The process flows in the “active” zone at a practically constant for a given moment temperature of particles in it. It is known that no technical work is done in an isobaric process and the gas enthalpy decrease is due to equivalent heat quantity output.

$$q_p = \Delta i_p \quad (5)$$

The heat lead away during constant pressure air cooling is consumed for: heating of material and evaporizing water to an average bed temperature; for the phase transition; for covering heat consumption for dry gas and saturated steams, produced at moisture evaporation, isothermal expansion, as well as for covering energy loss in the environment.

d) Isothermal mixing of wet gas and saturated steams separating during process. The process of mixing flows at a constant total pressure in the chamber and because of that, by increasing the moisture quantity input the wet gas (increasing of steam partial pressure in it) the dry gas steams partial pressure is decreased, i.e., the dry gas is expanded isothermally. The technical work done is compensated by means of an equivalent quantity of input heat.

$$q_{tv} = l_{t,tv} = R_v T \ln \frac{p_{v1}}{p_{v2}} = R_v T \ln \frac{p - p_{p1}}{p - p_{p2}} = R_v T \ln \frac{0,622 + d_2}{0,622 + d_1}. \quad (6)$$

The saturated steams that have been formed during moisture evaporation are expanded isothermally to the steams partial pressure in the air leaving the drying chamber.

$$q_{tp} = R_v T \ln \left(\frac{p_s}{p} \cdot \frac{0,622 + d_2}{d_2} \right). \quad (7)$$

A diagram describing the model mentioned above is presented on Fig. 2.

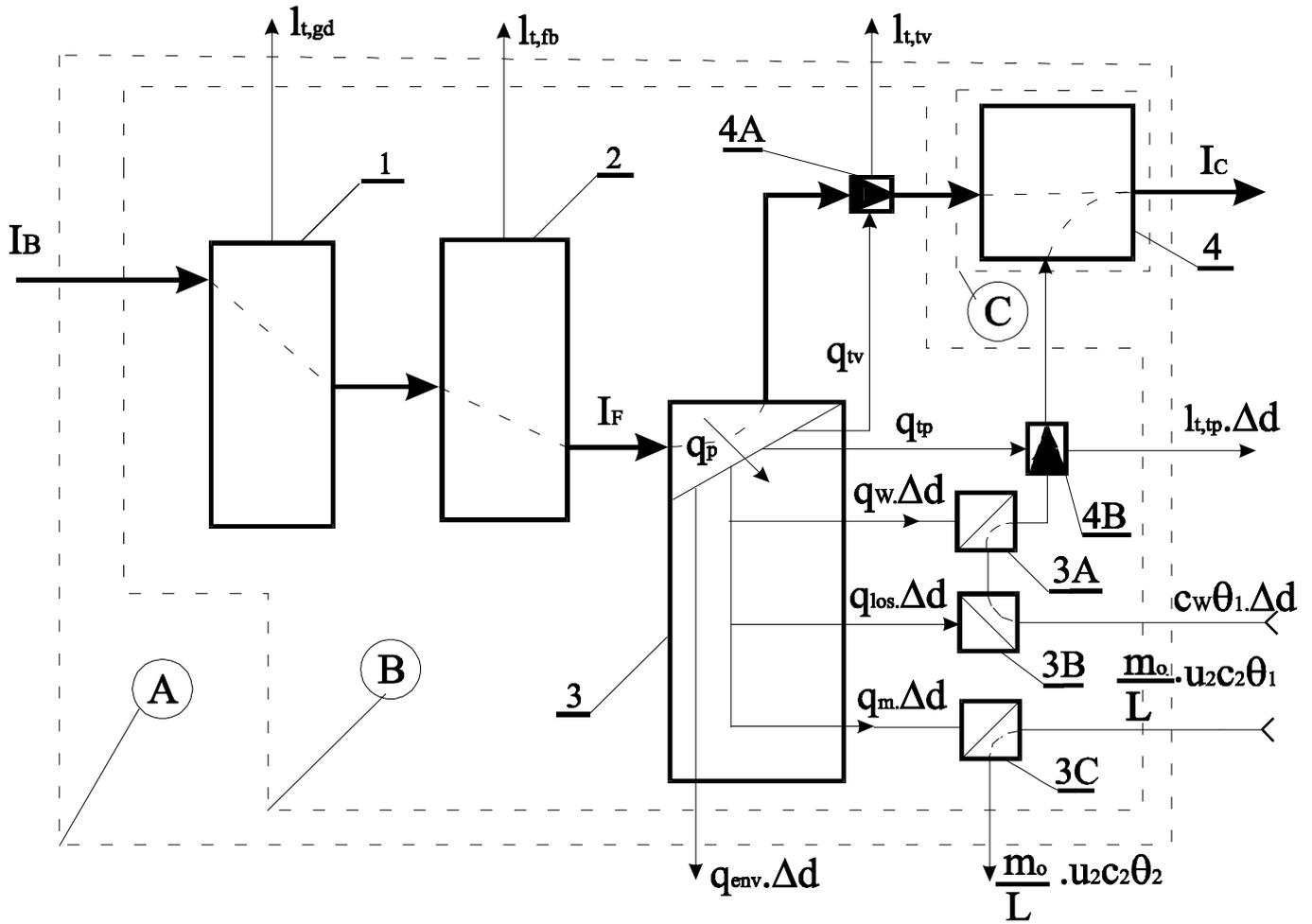


Fig.2

It has been accepted that in element 1 of the diagram the process of adiabatic expansion in the gas - distributor flows; the wet gas pressure fall in the gas-distributor decreases its enthalpy and is equivalent to a part of the technical work spent for the creation of fluidization of the bed. In element 2 the quasiisothermal expansion is carried out; the pressure fall of the wet gas during its passing through the bed leads to an additional enthalpy decrease and carrying out of a technical work for putting the particles into action. The third element illustrated the isobaric (constant - pressure) cooling of the gas and the allocation of the lead away from the gas heat stream. The heating of the dried material from its initial temperature θ_i to its temperature in the bed is carried out in the technical heat-exchanger 3C, and of the water that is dried - Δd in 3B. It has been accepted that in 3A takes place the process of moisture evaporation; at a constant temperature saturated vapours are produced. In element 4 of the diagram the preliminarily expanded isothermally dry gas and steams streams in 4A and 4B are mixed, and as a result a mixture with pressure equal to the total gas pressure at the drying chamber output has been obtained.

In case a balance is being made on a balance surface A (Fig. 2), by taking into consideration all input and output energy streams related to one kilogram of dry gas, respectively Δd kg of steam, according to the first law of thermodynamics, we shall obtain the equation:

$$I_B - I_C = (q_m + q_{env} - c_w \theta_1) \cdot \Delta d + \sum l_{t,i} \quad (8)$$

$$\text{when: } q_m \cdot \Delta d = (m_0 / L) \cdot u_2 c_2 (\theta_2 - \theta_1), \quad (8a)$$

$$\sum l_{t,i} = l_{t,gd} + l_{t,fb} + l_{t,lv} + l_{t,lp} \quad (8b)$$

Where the drying heat consumption, calculated for cooling of 1 kg of drying agent between the cross-sections B-B and C-C (q_L) (Fig. 1) can be expressed by the segment BG in I, d - diagram (Fig. 3) and can be determined by means of energy streams balance on a balance surface B.

$$I_B - I_G = c_{vd}(t_B - t_C) = (r + c_w \theta_2) \cdot \Delta d + \sum l_{t,i} + (q_m + q_{env} - c_w \theta_1) \cdot \Delta d \quad (9)$$

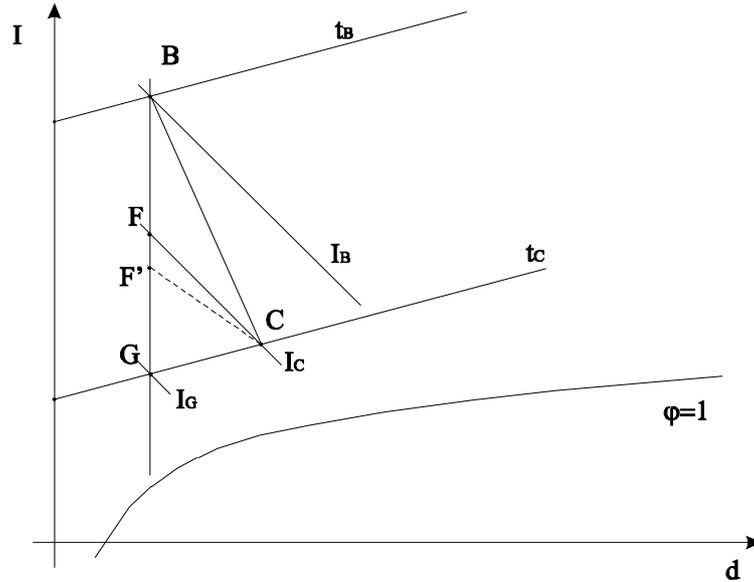


Fig. 3

The drying heat consumption, calculated according to the evaporated moisture in the bed (q_w) can be determined by means of a balance on a balance surface C (Fig. 2):

$$I_C - I_G = (r + c_w \theta_2) \cdot \Delta d. \quad (10)$$

In I, d - diagram can be expressed by the FG segment.

The difference between both heat consumptions - that calculated according to the drying agent cooling q_L and according to evaporated water quantity q_w is the real drying process correction, referred to 1 kg of dry air - Δ^I

$$\Delta^I = I_B - I_C = (q_m + q_{env} - c_w \theta_1) \cdot \Delta d + \sum L_{t,i} \quad (11)$$

or referred to 1 kg of evaporated water :

$$\Delta = \frac{\Delta^I}{\Delta d} = \Delta^I \cdot I = q_m + q_{env} - c_w \theta_1 + \frac{\sum L_{t,i}}{\Delta d} \quad (12)$$

where l is the specific air consumption for evaporizing 1 kg of water :

$$l = \frac{1}{d_c - d_B}. \quad (13)$$

The Expression (12) compared to (1) shows that when calculating the drying process the energy consumption utilized for doing the technical work at gas expansion has not been registered by now, that is lead away from the stream and is consumed for the purpose of creating boiling and increasing the velocity of the gas leaving the bed.

The thermodynamic analysis done shows that when calculating the wet air parameters change in the drying chamber, three new addends in the equation for determining the real drying process correction should be considered.

1. The energy losses in the gas-distributor q_{gd} :

$$q_{gd} = \frac{1}{\Delta d} \cdot \frac{\Delta p_{gd}}{\rho_B} = l \cdot \frac{R_{vd} T_B \Delta p_{gd}}{p_c + \Delta p_{gd} + \Delta p_{fb}} \quad (14)$$

2. The energy losses in the bed q_{fb} :

$$q_{fb} = \frac{1}{\Delta d} \cdot \frac{\Delta p_{fb}}{\rho_c} = l \cdot \frac{R_{vd} T \Delta p_{fb}}{p_c + \Delta p_{fb}} \quad (15)$$

3. The losses as a result of the dry gas isothermal expansion and saturated steams q_t :

$$q_t = \frac{1}{\Delta d} (q_{iv} + q_{ip} \cdot \Delta d) = l \cdot q_{iv} + q_{ip}, \text{ or}$$

$$q_t = l \cdot R_v T_C \ln \frac{0.622 + d_c}{0.622 + d_B} + R_p T_C \ln \left(\frac{p_s}{p_c} \cdot \frac{0.622 + d_c}{d_c} \right). \quad (16)$$

It is interesting to evaluate the process parameters influence and to compare according to their value the various addends of the real drying process correction :

a) Temperature mode influence - the three corrections q_{gd} , q_{fb} and q_t increase linearly increasing the input drying agent temperature in the bed.

b) The pressure in the drying chamber when drying in working at atmospheric pressure apparatuses, does not practically affect upon q_{gd} , q_{fb} and q_t . The effect of gas-distributor pressure drops and of the bed upon q_{gd} and q_{fb} is almost linear.

c) The gas constant of the wet air R_{vd} increases with increasing the input air d_B moisture content (for example, at a high degree of air recirculation) and affects upon q_{gd} and q_{fb} in the direction of their increase. A reciprocal but considerably weaker is the effect of d_B upon the correction q_t .

d) The moisture content increase of the air leaving the drying chamber is bilateral. At d_B fixed the d_c increase leads to a specific air consumption for drying l decrease and therefrom of the q_{gd} , q_{fb} , q_t correction, as well. The effect of d_c upon the second addend of q_t is analogical, as well.

From the analysis being made there follows that at a definite operation mode of the dryer, the new corrections proposed will have a more considerable effect in the processes of drying having a high specific air consumption. So, in a dryer that is able to dry 0.20 kg/s moisture from $m_2 = 2$ kg/s of material

passing through the dryer at a ratio of $L/m_2 = 20$ and temperature mode of $t_B = 80^\circ\text{C}$, $t_C = 50^\circ\text{C}$, $\theta_l = 20^\circ\text{C}$, and gas-distributor and bed pressure drops 1200 Pa each, the correction values will be as follows:

$q_{gd} = 241.3$ kJ/kg of evaporated moisture;

$q_{fb} = 223.5$ kJ/kg of evaporated moisture;

$q_t = 146.15 + 246.88 = 393.0$ kJ/kg of evaporated moisture;

$q_m = 1050$ kJ/kg of evaporated moisture;

$q_{env} \approx 70$ kJ/kg of evaporated moisture.

In the calculation mentioned above the following have been accepted: $d_B = 0.01$ kg/kg, $p_C = 100$ kPa, $c_2 = 1.25$ kJ/(kg.K), $\alpha_2 = 10$ W/(m².K), $F = 1$ m².

The example shows that the new corrections proposed can be compared with those conventionally included in the expression for calculating the real drying process correction, even they can surpass some of them and because of this they cannot be neglected.

All three new initiated energy losses have been applied in design of industrial sugar dryer.

NOTATION

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|------------|--|
| c_w | - specific heat capacity of the water, J/(kg.K) |
| c_v | - specific heat capacity at constant volume, J/(kg.K) |
| c_{vd} | - specific heat capacity of the wet air at constant volume, J/(kg.K) |
| d | - air humidity, kg water/kg humid air |
| F | - area, m ² |
| I | - enthalpy, J |
| L | - drying agent flux, kg/s |
| L_t | - technical work, J |
| I | - specific enthalpy, J/kg |
| l | - specific air consumption, kg/kg evaporated water |
| l_t | - specific technical work, J/kg |
| m | - material mass, kg |
| p | - pressure, Pa |
| Δp | - pressure drop, Pa |
| Q | - energy consumption, W |
| q | - specific heat, J/kg |
| R_p | - specific gas constant at constant pressure, J/(kg.K) |
| R_v | - specific gas constant at constant volume, J/(kg.K) |
| R_{vd} | - specific gas constant of humid air, J/(kg.K) |
| r | - heat of evaporation, J/kg |
| T | - gas temperature, K |
| t | - gas temperature, °C |
| v | - specific volume, m ³ /kg |

Greek symbols

| | |
|-----------|--|
| α | - heat transfer coefficient, W/(m ² .K) |
| Δ | - thermal correction for real drying process, J/kg |
| φ | - relative air humidity, % |
| ρ | - density, kg/m ³ |
| θ | - material temperature, °C |

Subscripts

add - additional heater
env - environment
gd - gas-distributor
fb - fluidized bed
fr - friction
loss - losses
m - material

p - isobaric
s - saturated vapour
t - isothermal
th - thermodynamic
tr - transport
v - isochoric

LITERATURE

Elenkov V.R., 1988, Drying and drying equipment. Zemizdat. Sofia, (bul).

Elenkov V.R., 1995, Jet-pulsed fluidized bed. Hydrodynamics. Kinetics of food and bioproducts drying and roasting in jet-pulsed fluidized bed. Doctor of Sciences Thesis. Plovdiv, (bul).

Ginzburg. A.S., 1985, Design and calculations of dryers for food industry. Agropromizdat. Moscow, (rus).

Pakowski Z., Mujumdar A.S., 1987, Basic process calculations in drying. Handbook of industrial drying. Marcel Dekker. Montreal.