Convection Drying in the Food Industry

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ABSTRACT

Experimental and theoretic research was conducted and the results were implemented in a real industrial environment on a convection dryer with pneumatic transport of material. The numeric values are given for optimum parameters of drying, energetic characteristics and balances as well as the models of heat transfer. Accomplishment of the heat transfer in these systems is based on the principle of direct contact of dried material and warm air. Then, an intensive transfer of heat and mass is accomplished. This work presents the results of research which can be useful in designing and construction of such dryers in the food industry. It refers to the technical and engineering characteristics of the dryer, energetic balances and coefficients of heat transfer.

Key words: Drying, convection, heat transfer, numeric data, food processing.

1. INTRODUCTION

Application of the convection pneumatic dryers is represented especially in food industry in plants for industrial processing of grains (wet milling processing of wheat and corn). Generally, such dryers can be used for drying of meal-like and fine-kernel materials. Simple construction and a relatively low consumption of energy have enabled successful application of such dryers in the above stated industrial branches. The construction of the convection dryer enables simultaneous pneumatic transport of wet material and its drying.

In these dryers, a continuous drying of loose materials is being made, the concentration being (0, 05-2,00) kg of material per 1 kg of air. Average particle size of the drying material can be (0, 05-2,00) mm. The circulation speed of the heated agent of drying (air or gas) in the dryer is (10-30) ms^{-1}. The initial moisture of the material dried can be w_1= (35-40) %, and the remaining moisture after drying is usually w_2 = (10-15) %. The specific consumption of energy is usually (3900-5040) kJ kg^{-1}, of evaporable water. Efficiency of such dryers is evaluated according to the thermal degree of utilization which is within the limits of (66-75) %, depending of the drying system (indirect or direct drying). The quantity of evaporated moisture in the dryer pneumatic pipe is approximately (300-350) kg $m^{-3}h^{-1}$. The drying time in these dryers is very short, only several seconds, therefore they can be used for drying of the materials susceptible to high temperatures in a short drying period of time.

2. DESCRIPTION OF EXPERIMENTAL PLANT

Experimental research is made in the convection pneumatic dryer, Figure 1. Drying agents are heated with the gas burner (1). Drying is performed in the direct contact of warm gases with the moist material. The principle of direct drying is represented here. The drying material is corn bran.

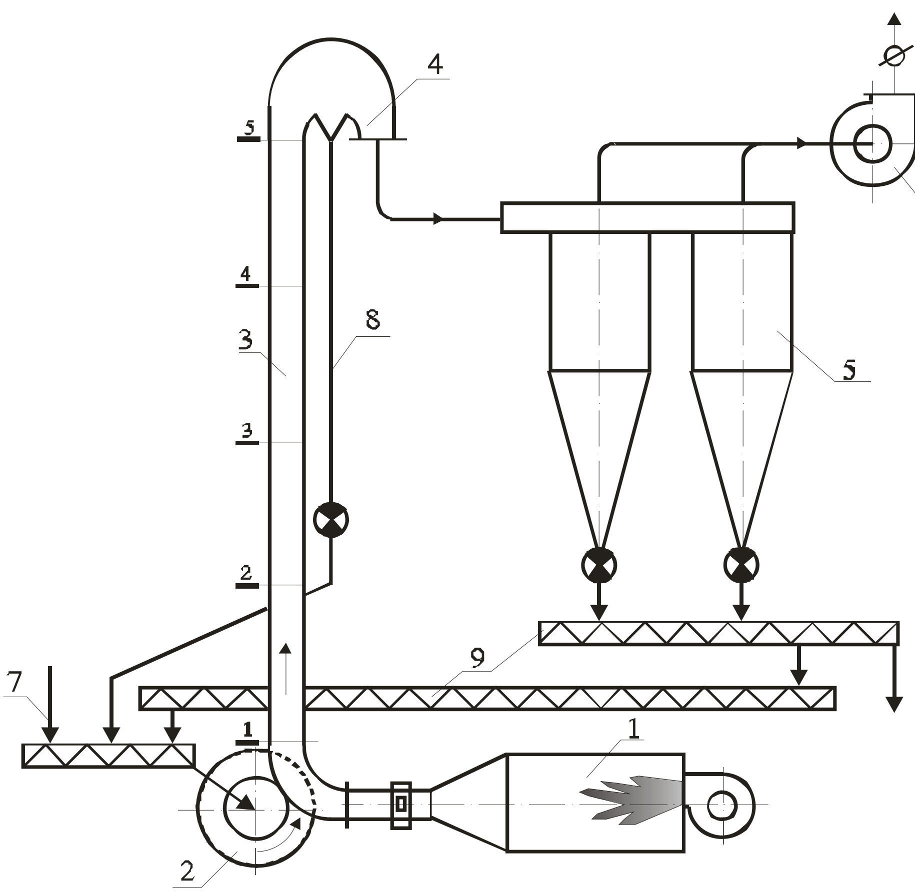

Figure 1. Scheme of experimental drying equipment: 1 – gas burner, 2 – rotation dozer of moist material, 3 – dryer pipe, 4 – dryer head, 5 – cyclones, 6 – centrifugal ventilator, 7 – auger for bringing of moist material, 8 – pipe for recycling of material, 9 – auger conveyer.

Dosing of moist material to the dryer is performed through the rotation dozer (2) with the capacity of m_1 = 1640 kg h^{-1}, through the auger conveying system, as given in the scheme of experimental equipment in Figure 1. Auger conveyers have a role of mixing the moist material with the dried material from the pipeline for recirculation (8). In such a way, a homogenous moist material is obtained at the dryer inlet. In the table 1, the characteristics of convection pneumatic dryer are given.

Table 1. Characteristics of convection pneumatic drying

No.	Position	Name of equipment and characteristics
1	1	Gas burner type: Saacke SG, heat power Q= 3,40 MW
2	3	Dryer pipe, diameter d=625 mm, height 21 m
3	5	Cyclone separator, diameter Dc=1350 mm, height: cylindrical part of the cyclone is 1920 mm, conical part of cyclone is 3350 mm
4	6	Centrifugal ventilator: V=26000 $m_n^3h^{-1}$, p=3500Pa, N=75kW
5	7	Rotating dozer, N=18.5kW, n=660 min^{-1}
6	4	Dryer head

Moist material is transported via hot air – the drying agent through the dryer pneumatic pipe (3), it passes through the dryer head (4) and goes to the cyclone separators (5) for separation of dried material, and the hot gases are expelled by a ventilator (6), into the atmosphere. The material which is not dried completely falls into the conical bottom of the dryer head (4) due to the higher content of moisture, the gravitation takes it back to additional drying through the pipeline (8). The dried material is transported from the cyclone via auger conveyors and through a separate line of pneumatic transport up to the material warehouse department. During drying, the determined fuel - gas consumption is B = 293 m^3h^{-1}.

Table 2 contains average values of the results of measuring the air temperature – the drying agent and moisture of dried material. Experimental measuring is being made in the approximate stationary conditions of the dryer operation. The stationary conditions mean the stationary conditions during a longer period of the dryer operation and greater number of measuring (where non-stationary conditions of the process are excluded during the realistic conditions of the dryer operation).

Table 2. Average values of the results of measuring the drying temperature and the material moisture

Measuring place, according to the figure 1	1-1	2-2	3-3	4-4	5-5
Temperature of the hot air, t ˚C	425	342	222	155	110
Moisture of the dried materijal, w %	30	22	16	14	12

3. A DETERMINATION METHOD OF THE ENERGETIC BALANCE AND COEFICIENT OF THE HEAT TRANSFER

In the drying process, the total invested energy is spent on: water evaporation, heating of drying material and heat losses. Energetic balances show appropriate relations between the total invested energy, utilized energy and heat losses during the drying process. The energetic balances can be useful when showing the dryer condition diagnosis.

The difference in the air enthalpy at the inlet and at the outlet of the dryer:

$$\Delta H = H_1 - H_2 = c_p(t_1 - t_2) \quad kJm_n^{-3} \tag{1}$$

Quantity of evaporated water:

$$W = m_1\left(1 - \frac{100 - w_1}{100 - w_2}\right) \quad kgh^{-1} \tag{2}$$

Total heat quantity:

$$\dot{Q}_U = \dot{Q}_w + \dot{Q}_S + \dot{Q}_g \quad kJh^{-1} \tag{3}$$

$$\dot{Q}_U = B\,H_d\,\eta_T \quad kJh^{-1} \tag{4}$$

Quantity of drying air:

$$V_L = \frac{\dot{Q}_U}{\Delta H} \qquad m_n^3 h^{-1} \tag{5}$$

Specific consumption of energy:

$$q = \frac{\dot{Q}_U}{W} \qquad kJkg^{-1} \tag{6}$$

Thermal degree of utilization:

$$\eta_T = \frac{t_1 - t_2}{t_1} = \frac{\dot{Q}_U - \dot{Q}_g}{\dot{Q}_U} \tag{7}$$

Total heat power of drying:

$$Q_U = h_u\, A\, \Delta t_{sr} \quad W \tag{8}$$

Total coefficient of the heat transfer:

$$h_u = Q_U / (A\, \Delta t_{sr}) \quad Wm^{-2}K^{-1} \tag{9}$$

Heat for drying, i.e. its convective part consists of the heat for water evaporation (Q_w) and heat for heating of the drying material (Q_s), meaning, without heat losses (Q_g):

$$\dot{Q}_{conv} = \dot{Q}_W + \dot{Q}_S \quad kJh^{-1} \tag{10}$$

During convective drying the following equation of the heat transfer is applied as well:

$$\dot{Q}_{conv} = h_c \cdot A \cdot \Delta t_{sr} \qquad W \tag{11}$$

Coefficient of the heat transfer through convection (h_c) is a relevant parameter of Nusselt criteria of heat transfer:

$$N_u = \frac{h_c \cdot d}{k} \tag{12}$$

Based on the analysis of influential parameters of heat transfer, the following equation is being acquired of Nusselt type:

$$h_c = \frac{k}{d} K \left(\frac{d \cdot G}{\mu} \right)^a \tag{13}$$

Based on it, the research results can be shown with the help of correlation equation of Nusselt type:

$$N = K(R_e)^a \tag{14}$$

Reynolds number is being determined with the following equation:

$$R_e = \frac{d \cdot G}{\mu} \tag{15}$$

The constant (K) and the exponent (a) are being determined by the method of the least difference squares.

4. THE RESULTS OF EXPERIMENTAL RESEARCH OF ENERGETIC BALANCE HEAT TRANSFER COEFFICIENTS AND DISCUSSION

Experimental research on the convection pneumatic dryer, Figure 1., was aimed at determining the energetic balance, specific consumption of energy, thermal degree of utilization and other relevant parameters of drying, according to the literature (Prvulovic, 2004). The results of the energetic balance are given in the Table 3.

Table 3. Energy balance of convection pneumatic dryer

No.	Energy drying parameter	Sign and measure unit	Energy value parameter
1	Air temperature at the inlet of dryer	t_1 ˚C	425
2	Quantity of evaporable water	W kg h^{-1}	2030
3	Total heat quantity	Qu kJ h^{-1}	7956000
4	Drying heat power	Qu kW	2210
5	Energy specific use	q kJ kg^{-1}	3919
6	Quantity of drying air	V_L $m_n^3h^{-1}$	19452
7	Specific quantity of evaporable water	kg $m^{-2}h^{-1}$	49
8	Specific quantity of evaporable water	kg $m^{-3}h^{-1}$	315
9	Air temperature at the outlet of the dryer	t_2 ˚C	110
10	Thermal degree of utilization	η_T %	74

Based on the research, the total heat force of drying of Q= 2210 kW, is being acquired as well as the specific consumption of energy q = 3919 kJ kg $^{-1}$, of evaporable water. According to the literature (Heβ, 1984; Tolmac, 1997; Prvulovic, 2001) a specific consumption of energy in convection drying amounts (3850 – 5040) kJ kg $^{-1}$, of evaporable water. According to the data from literature (Islam, *et. ol.* 2004), specific consumption of energy amounts q = (4642 – 5283) kJ kg $^{-1}$, of evaporable water.

On the basis of the results of energetic balance and results of the drying parameters measuring, according to the literature (Prvulovic, 2004), the total coefficient of the heat transfer during convection drying is h_u = 342 $Wm^{-2}K^{-1}$, Table 4. On the basis of the research results, the mass air flow amounts 0,169 kg $s^{-1}m^{-2}$, the drying capacity is 1640 kg h^{-1}, and the air temperature at the dryer inlet is 425°C. According to the literature (Lin *et al.,* 1999.), the mass air flow is 0,289 kg $s^{-1}m^{-2}$, the drying capacity is 1152 kg h^{-1}, at the drying temperature of 90°C.

Table 4. Total coefficient of heat transfer (h_u)

Total quantity heat (heat power) Qu kW	Volume of pipe drying place Vk m^3	Drying surface A m^2	Middle log. difference of temperature Δt_{sr} °C	Total heat transfer coefficient h_u $Wm^{-2}K^{-1}$
2210	6,44	41,20	157	342

According to the research (Heβ, 1984, Lambic, 1998; Tolmac, 1997), on the convection pneumatic dryer, the value of the total coefficient of heat transfer in the process of drying corn starch is 308 $Wm^{-2}K^{-1}$, and in drying of potato starch the coefficient of heat transfer is 320 Wm-

$^{2}K^{-1}$. The coefficient of heat transfer under the dynamic conditions of the dryer operation (non-equal dosing of material to be dried, oscillations in the initial moisture content, temperature of drying, heat flux, etc.) depends on the greater number of different values which characterize the heat transfer. The objective of this part of research is to determine the character of heat transfer in such complex dynamic model, considering that the heat transfer comprises a phenomenon of heat transfer by convection, conduction and radiation. Based on the results of research, the value of the coefficient of heat transfer by convection has been determined, Table 5.

Table 5. Coefficient of heat transfer by convection (h_c)

Heat power for water evaporation Q_w kW	Heat power for material heating Q_s kW	Heat power of heat transfer by convection Q_{conv} kW	Surface drying A m^2	Mean logarithmic difference of temperature Δt_{sr} ^0C	Coefficient of convection heat transfer h_c $Wm^{-2}K^{-1}$
1	2	3	4	5	6
1502	67	1569	41,20	157	242

Values of the Reynold's and Nusselt's number are given in the Table 6.

Table 6. Reynold's number and Nuselt's number

Mass speed stream air G kg $s^{-1}m^{-2}$	Dryer pipe diameter d m	Dynamic visc. of air $\mu x10^{-6}$ kg $s^{-1}m^{-1}$	Reynold's number $R_e x10^{-2}$	Coefficient of convection heat transfer h_c $Wm^{-2}K^{-1}$	Thermal air conductivi-ty k $Wm^{-1}K^{-1}$	Nusselt's number N_u
1	2	3	4	5	6	7
0,169	0,625	34,05	31	242	5,34	28,32
0,169	0,625	31,09	34	242	4,86	31,12
0,169	0,625	26,73	39	242	4,07	37,16
0,169	0,625	23,97	44	242	3,60	42,01
0,169	0,625	22,38	47	242	3,27	46,25
0,169	0,625	27,64	39	242	4,23	36,97

According to the research results, the criteria equation of the Nusselt type has the following form:

$$N_u=-6.385 + 0.011R_e \qquad (16)$$

Based on the relation (16), the results of the experimental and theoretic researches are correlated by the relation between the Nusselt's number (N_u) and Reynold's number (R_e). Based on it, by increasing of the Reynold's number due to the increase of hot air circulation – the drying agent, the Nusselt's number is increased. The coefficient of the heat transfer by convection (h_c) is increased then. On the basis of the experimental research, the following relation is acquired for the coefficient of heat transfer by convection:

$$h_c = \left(-6{,}385 + 0{,}011 \cdot R_e\right) \cdot \frac{k}{d} \tag{17}$$

Table 7 contains the values of the coefficient of the heat transfer (h_c) for the various values of the Reynold's number. By application of the correlation theory, the method of the least difference squares on the results of experimental and theoretic research, we acquire the phenomenology equations of the dependence of the heat transfer coefficient (h_c) and the Reynold's number (R_e).

Table 7. Heat transfer coefficient (h_c), for different values of Reynold's number and diameters of the dryer pipe d=0.625m

Reynold's number Re	Air temperature t °C	Thermal air conductivity k $Wm^{-1}K^{-1}$	The dryer pipe diameter d m	Coefficient of convection heat transfer h_c $Wm^{-2}K^{-1}$
1	2	3	4	5
3000	400	5,21	0,625	222
3500	300	4,60	0,625	230
4000	200	3,93	0,625	236
4500	150	3,56	0,625	245
5000	110	3,21	0,625	250
5500	100	3,10	0,625	257

The empirical equation of dependence of the heat transfer coefficient (h_c) and the Reynold's number (R_e) for the diameter of the dryer pipe d = 0,625 m, is given by the following relation:

$$h_c = 179.8 + 0.014 \cdot Re \tag{18}$$

On the basis of the results of research acquired in the Table 4. the total coefficient of the heat transfer h_u = 342 $Wm^{-2}K^{-1}$. The coefficient of the heat transfer by convection h_c = 242 $Wm^{-2}K^{-1}$ is given in Table 5. The largest quantity of heat during drying is consumed for heating of the material to be dried and water evaporation. Coefficient of heat transfer by convection h_c = 242 $Wm^{-2}K^{-1}$ in the complex conditions of the dryer operation depends on the various values which characterize the heat transfer.

These values are the heat flux, the area of drying, the temperature differences, etc. In order to determine the effects of the heat transfer during convection drying, the topic of heat losses is reviewed as well. On the basis of that, as a separate value, the coefficient of the heat transfer has been determined h_u-h_c =100 $Wm^{-2}K^{-1}$ which shows the share of the heat losses through the air outflow from the dryer and the losses due to conduction and radiation through the dryer pipe.

5. CONCLUSION

This work presents the experimental and theoretic research of relevant parameters of drying on the convection pneumatic dryer in the food industry. Based on the analysis of energetic balance, the heat force of drying has been determined Q_u = 2210 kW, specific consumption of energy q = 3918 kJ kg^{-1} of evaporable water, as well as the thermal degree of utilization η_T = 0,74. Energy balance of the dryer can serve in evaluation of power condition of the dryer as well as in reviewing of the possibility of rational consumption of energy. A significant share of the energy during drying is forwarded to transfer of heat to the material, necessary for evaporation of moisture and heat for the breaking of connection forces of moisture with the basis of the material to be dried. Specific consumption of energy and quality of dried material are basic data which characterize the results of drying on the convection dryer. By following and control of these parameters in the drying process, the optimum consumption of energy is provided as well as the quality of dried material.

On the basis of the results of research of energetic balance and the results of measuring the temperature of the drying agent, the total coefficient of the heat transfer is being determined in the convection dryer in the amount of h_u = 342 $Wm^{-2}K^{-1}$, and the coefficient of the heat transfer by convection h_c = 242 $Wm^{-2}K^{-1}$. The effects of the heat losses during drying are expressed through the separate value $h_u – h_c$ = 100 $Wm^{-2}K^{-1}$, so called coefficient of the heat transfer for the heat losses together with the outlet air and the heat transfer by conduction and radiation through the dryer pipe. In such a way the effects of the heat transfer are determined as well as the basic parameters of the heat transfer.

The acquired results of research are based on the experimental data from the industrial dryer. Based on that, the results of research have a value of use, i.e. they are useful to the designers, manufacturers and beneficiaries of these and similar drying systems as well as for the educational purposes. The results of research can also be used for: determination of dependence and parameters of the heat transfer during convection drying, as well as in designing and development of convection dryers.

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NOMENCLATURE

Nu – Nusselt's number

Re – Reynold's number

d – the dryer pipe diameter, mm

k – thermal air conductivity, $Wm^{-1}K^{-1}$

G – mass speed stream air, $kg\ s^{-1}m^{-2}$

μ – dynamic viscosity warm air, $kg\ s^{-1}m^{-1}$

h_u – coefficient of heat transfer, $Wm^{-2}K^{-1}$

h_c - coefficient of convection heat transfer, $Wm^{-2}K^{-1}$

H – enthalpy, $kJ\ kg^{-1}$

t_1 – air temperature at the inlet of dryer, °C

t_2 – air temperature at the outlet of dryer, °C

c_p - specific air heat, $kJm_n^{-3}K^{-1}$

W – quantity of evaporated water, $kg\ h^{-1}$

m_1 – quantity of moist material, $kg\ h^{-1}$

w_1 – content of the wet material at the inlet of dryer, %

w_2 – content of the wet material at the outlet of dryer, %

Δt_{sr} – mean logarithm difference of temperature, °C

Q – heat quantity, $kJ\ h^{-1}$

B – fuel gas consumption, m^3h^{-1}

H_d – lower gas heat power, $kJ\ m^{-3}$

A – drying surface, m^2

V_k – volume of dryer pneumatic pipe, m^3

Q_w - heat for water evaporation, $kJ\ h^{-1}$

Q_s - heat for heating of the drying material, kJ h^{-1}

Q_g - heat losses, kJ h^{-1}

η_T - thermal degree of utilization