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Experimental and Numerical Studies of Heat Transfer and Kinetic Drying of Convection Pneumatic Dryer

This paper presents the results of research which can be useful in designing and construction of such dryers in food industry. It refers to the technological and technical characteristics of the dryer, energy balances, coefficients of heat transfer and kinetic drying. The accomplishment of 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. Experimental and theoretical research was conducted and the results were implemented in real industrial environment on convection dryer with pneumatic transport of material. The numeric values are given for optimum parameters of drying, energy characteristics and balances as well as the models of heat transfer.

Keywords: *kinetic drying, heat transfer, convection dryer, numerical data.*

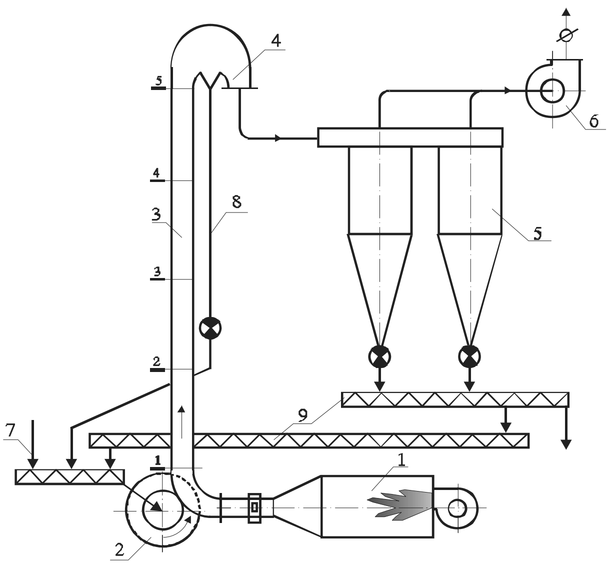
1. INTRODUCTION

The application of 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 meal-like and fine-kernel materials. Simple construction and relatively low consumption of energy have enabled successful application of such dryers in the above mentioned industrial branches. The construction of a convection dryer enables simultaneous pneumatic transport of wet material and its drying. Heat transfer systems of such kind and likewise were introduced in literature [1-5].

In accordance with the literature [6-10] in these dryers, a continuous drying of loose materials is done, 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 kJkg^{-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 kgm^{-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. EXPERIMENTAL PLANT AND MEASUREMENT RESULTS

Experimental research was made in the convection pneumatic dryer, Fig. 1. Drying agents were heated with the gas burner (1). Drying was 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.



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

Figure 1. Experimental plant scheme

Dosing of moist material to the dryer is performed through the rotation dozer (2) with the capacity of m_1 = 9925 kgh^{-1}, through the auger conveying system, as given in the scheme of experimental equipment in Figure 1. The role of the auger conveyers (7) is to mix the moist material. 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.

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

Received: April 2011, Accepted: August 2011
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hot gases are expelled by a ventilator (6), into the atmosphere. The dried material is transported from the cyclone via auger conveyors (9). During drying, the determined fuel – gas consumption is $B = 290\ m^3h^{-1}$.

Table 1. Characteristics of convection pneumatic dryer

No.	Pos.	Name of equipment and characteristics
1	1	Gas burner type: Saacke SG, heat power $Q = 3.40$ MW
2	2	Rotating dozer $N = 18.5$ kW, $n = 660\ min^{-1}$
3	3	The dryer pipe diameter $d = 625$ mm, height $h = 21$ m
4	4	Dryer head
5	5	Cyclone separator diameter $D_c = 1350$ mm
6	6	Centrifugal ventilator $V = 26{,}000\ m_n^3h^{-1}$, $\Delta p = 3500$ Pa, $N = 75$ kW

Table 2 contains average values for the results of measuring the air temperature – the drying agent and moisture of dried material. Experimental measuring is 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 real conditions of the dryer operation).

Table 2. Average values for 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
Air temperature at the inlet of dryer, T_1 [°C]	425	342	222	155	110
Moisture of the dried material, w [%]	30	22	16	14	12

3. BUDGET THEORY

In the drying process, the total invested energy is spent on: water evaporation, heating of drying material and heat losses. Energy balances show appropriate relations between the total invested energy, utilized energy and heat losses during the drying process. The energy 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 is:

$$\Delta H\ [\mathrm{kJm_n^{-3}}] = C_p (T_1 - T_2)\,. \tag{1}$$

The amount of water evaporated:

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

Total heat quantity:

$$\dot{Q}_\mathrm{U}\ [\mathrm{kJh^{-1}}] = \dot{Q}_\mathrm{w} + \dot{Q}_\mathrm{s} + \dot{Q}_\mathrm{g} \tag{3}$$

$$\dot{Q}_\mathrm{U}\ [\mathrm{kJh^{-1}}] = B H_\mathrm{d} \eta_\mathrm{T}\,. \tag{4}$$

The amount of air for drying:

$$V_L\ [\mathrm{m_n^{-3}h^{-1}}] = \frac{\dot{Q}_\mathrm{U}}{\Delta H}\,. \tag{5}$$

Specific energy consumption:

$$q\ [\mathrm{kJh^{-1}}] = \frac{\dot{Q}_\mathrm{U}}{W}\,. \tag{6}$$

Thermal efficiency:

$$\eta_\mathrm{T} = \frac{T_1 - T_2}{T_1} = \frac{\dot{Q}_\mathrm{U} - \dot{Q}_\mathrm{g}}{\dot{Q}_\mathrm{U}}\,. \tag{7}$$

Thermal drying power:

$$Q_\mathrm{U} = h_\mathrm{u} A \Delta T_\mathrm{sr} W\,. \tag{8}$$

Overall coefficient of heat transfer:

$$h_\mathrm{u}\ [\mathrm{Wm^{-2}K^{-1}}] = \frac{Q_\mathrm{U}}{A \Delta T_\mathrm{sr}}\,. \tag{9}$$

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):

$$\dot{Q}_\mathrm{conv}\ [\mathrm{kJh^{-1}}] = \dot{Q}_\mathrm{w} + \dot{Q}_\mathrm{s}\,. \tag{10}$$

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

$$\dot{Q}_\mathrm{conv}\ [\mathrm{W}] = h_\mathrm{c} A \Delta T_\mathrm{sr}\,. \tag{11}$$

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

$$Nu = \frac{h_\mathrm{c} d}{k}\,. \tag{12}$$

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

$$h_\mathrm{c} = \frac{k}{d} \mathrm{K} \left(\frac{dG}{\mu} \right)^\mathrm{a}. \tag{13}$$

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

$$Nu = \mathrm{K} (Re)^\mathrm{a}\,. \tag{14}$$

The Reynolds number is being determined with the following equation:

$$Re = \frac{dG}{\mu}\,. \tag{15}$$

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

4. TEST RESULTS

Experimental research on the convection pneumatic dryer, Fig. 1, was aimed at determining the energy balance, specific consumption of energy, thermal degree of utilization and other relevant parameters of drying. The results of the energy 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	Amount of water evaporated	W [kgh^{-1}]	2030
3	Total quantity of heat	Q_u [kJh^{-1}]	7,956,000
4	Thermal drying power	kW	2210
5	Specific energy consumption	q [kJkg^{-1}]	3920
6	Quantity of drying air	V_L [m$_n^{-3}$h^{-1}]	19500
7	Specific amount of water evaporated	[kgm^{-2}h^{-1}]	41.3
8	Amount of air for drying	V_L [m$_n^3$h^{-1}]	14,430
9	Air temperature at the outlet of dryer	T_2 [°C]	110
10	Thermal efficiency	η_T	0.74

Based on the research, the total heat force of drying of Q = 2210 kW, is acquired as well as the specific consumption of energy q = 3920 kJkg^{-1}, of evaporable water. According to the literature Heβ [2] and Tolmač [4], a specific consumption of energy in convection drying amounts to 3650 – 5040 kJkg^{-1} of evaporable water. According to the data from literature Islam [11], specific consumption of energy amounts to q = 3640 – 5280 kJkg^{-1} of evaporable water.

On the basis of the results of energy balance and results of the drying parameters measuring, the overall coefficient of heat transfer during convection drying is h_u = 340 Wm^{-2}K^{-1}, Table 4. On the basis of the research results, the mass air flow amounts to 0.169 kgs^{-1}m^{-2} and the air temperature at the dryer inlet is 425 °C. According to the literature Liu [12], the mass air flow is 0.289 kgs^{-1}m^{-2}, the drying capacity is 1152 kgh^{-1}, at the drying temperature of 90 °C.

According to the research by Prvulovic [13] and Sun [14], on the convection pneumatic dryer, the value of the overall coefficient 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}.

Table 4. Overall coefficient of heat transfer (h_u)

Total quantity heat (heat power), Q_u [kW]	Volume of dryer pneumatic pipe, Vk [m^3]	Drying surface*, A [m^2]	Logarithmic mean temperature difference, ΔT_{sr} [°C]	Overall heat transfer coefficient, h_u [Wm^{-2}K^{-1}]
2210	6.44	41.20	158	340

*According to [2,6] drying surface is equal to interior surface of drying pipe ($A = d\pi h$; d = 0.625 m – pipe diameter; h = 21 m – pipe height).

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.

Values of the Reynolds and Nusselt number are given in the Table 6.

Table 7 contains the values of the coefficient of heat transfer (h_c) for various values of the Reynolds number. By application of the correlation theory, the method of the least squares difference for the results of experimental and theoretical research, we acquire the phenomenology equations of the dependence of the heat transfer coefficient (h_c) and the Reynolds number (Re).

For drying agents flow (heat air) through the dryer pneumatic pipe V_T = 14,430 m$_n^3$h^{-1} and the pipe dryer diameter d = 625 mm, the transport rate is v_n = 13 ms^{-1}. As for the length (height), the drying pneumatic pipe is h = 21 m and drying time is t = 1.616 s.

Table 5. Convection heat transfer coefficient (h_c)

Amount of heat for evaporation of water, Q_w [kW]	Amount of heat for heating the material, Q_s [kW]	Amount of heat transfer by convection, Q_{conv} [kW]	Drying surface, A [m^2]	Logarithmic mean temperature difference, ΔT_{sr} [°C]	Convection heat transfer coefficient, h_c [Wm^{-2}K^{-1}]
1	2	3	4	5	6
1500	68	1568	41.2	158	240

Table 6. Reynolds number and Nusselt number

Mass air speed, G [kgs^{-1}m^{-2}]	The dryer pipe diameter, d [m]	Dynamic visc. of air, $\mu \times 10^{-6}$ [kgs^{-1}m^{-1}]	Reynolds number, $Re \times 10^{-2}$	Convection heat transfer coefficient, h_c [Wm^{-2}K^{-1}]	Thermal air conductivity, k [Wm^{-1}K^{-1}]	Nusselt number, Nu
1	2	3	4	5	6	7
0.169	0.625	34.05	31	240	5.34	28.32
0.169	0.625	31.09	34	240	4.86	31.12
0.169	0.625	26.73	39	240	4.07	37.16
0.169	0.625	23.97	44	240	3.60	42.01
0.169	0.625	22.38	47	240	3.27	46.25
0.169	0.625	27.64	39	240	4.23	36.97

Table 7. Convection heat transfer coefficient (h_c) for different values of the Reynolds number and diameters of the dryer pipe d = 0.625 m

Reynolds number, *Re*	Air temperature, T [°C]	Thermal air conductivity, k [$Wm^{-1}K^{-1}$]	The dryer pipe diameter, d [m]	Convection heat transfer coefficient, 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 Figure 2, presenting drying curves, demonstrates the dependency of moisture, changes on drying time. At the beginning of the drying period, the dependency of moisture changes and drying time have almost linear character, whose adequate drying period is t = 0 – 0.75 s. This is the first drying period and drying rate is constant. In the second drying period, in the time interval t = 0.75 – 1.616 s, the dependency of moisture changes and drying time does not have linear character, which is demonstrated by the polynomial of the second kind. In the end of the drying process, the percent of balanced moisture is w_2 =12 %.

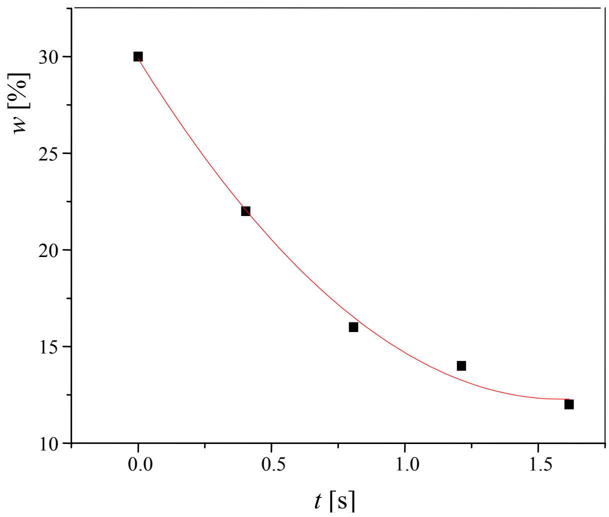

Figure 2. Drying curves

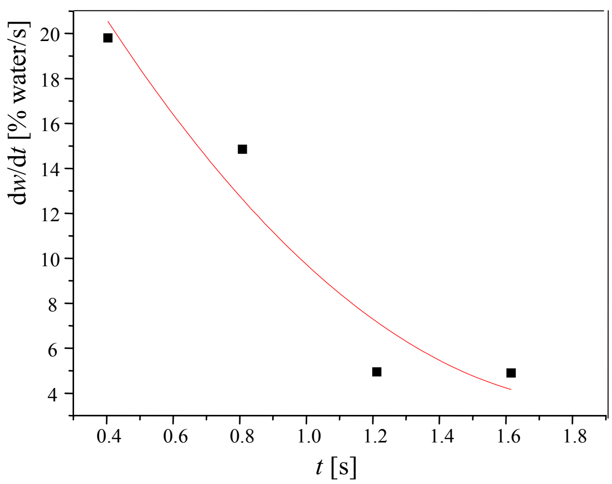

Figure 3. Drying rate curves

The Figure 3 presents drying rate curves. The first stage of drying rate is constant, however, in the second stage it drops. When the material moisture is reduced to the balanced moisture w_2 = 12 %, the moisture evaporation rate is dw/dt = 5 [% water/s].

The Figure 4 presents thermal drying curves. The dependency of changes of thermal drying agents and drying time is demonstrated by the polynomial of the second kind. In the drying process, during pneumatic transport of the drying material, the degree of concentration has relatively low value, c_k = 0.393 kg material/kg air], so it can be taken as an aspect of pure drying agents transport. Thermal drying curves, see Figure 4, can have thermal approximate linear character. At the start of the drying period the temperature of drying agents is 425 °C and at the end of drying it is 110 °C.

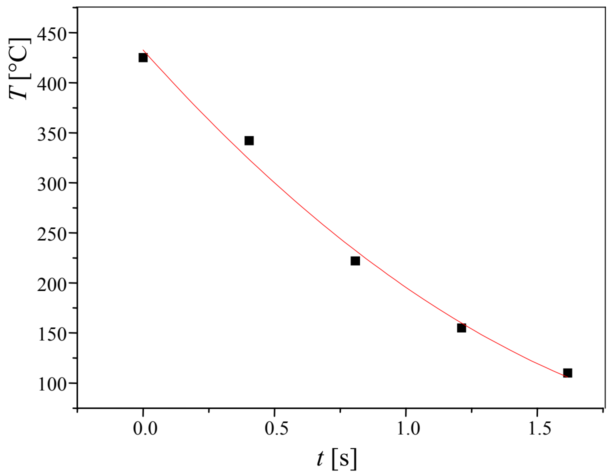

Figure 4. Thermal drying curves

By using the theory of correlation – the method of least squares in processing the experiment data, the next empiric equations are obtained:

- equation of material moisture dependency from drying time:

$$w = 29.88 - 22.20t + 7.00t^2 \quad (16)$$

- equation of drying rate dependency from time:

$$\frac{dw}{dt} = 30.90 - 28.67t + 7.50t^2 \quad (17)$$

- equation of thermal drying curves:

$$T = 432 - 293.45t + 56.45t^2 . \quad (18)$$

The obtained empiric equations based on experimental research define the nature of the drying process course. Dependency of drying rate change and material moisture as is presented in Figure 5.

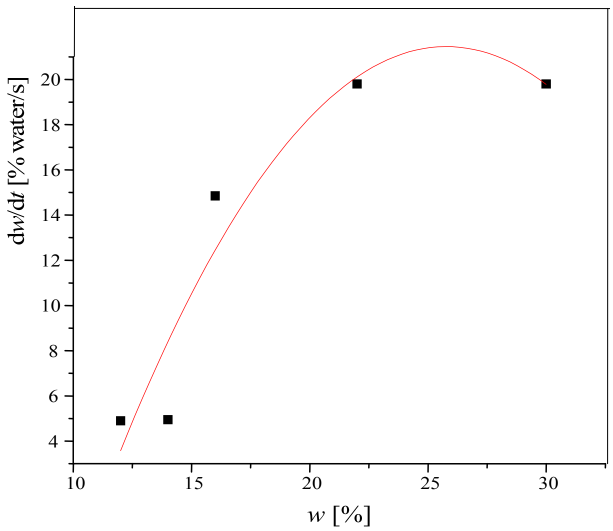

Figure 5. Drying rate and material humidity dependency

Applying the correlation theory, the least square method to the results of research, a correlation equation is obtained:

- equation of drying rate dependency and material moisture:

$$\frac{dw}{dt} = -41.10 + 4.85w - 0.094w^2 . \qquad (19)$$

5. DISCUSSION

Based on the Table 6, the results of the experimental and theoretical researches are correlated by the relation between the Nusselt number (*Nu*) and the Reynolds number (*Re*). Based on it, by increasing the Reynolds number due to the increase of hot air circulation – the drying agent, the Nusselt number is increased. The coefficient of heat transfer by convection (h_c) is increased then. This is according to the research by Herman [15], Tolmac [8] and Sampaio [5].

On the basis of the results of research presented in the Table 4, the overall coefficient of the heat transfer is h_u = 340 $Wm^{-2}K^{-1}$. The coefficient of the heat transfer by convection h_c = 240 $Wm^{-2}K^{-1}$ is given in Table 5. The largest quantity of heat during drying is consumed for heating of the material to be dried and for water evaporation. The coefficient of heat transfer by convection h_c = 240 $Wm^{-2}K^{-1}$ in the complex conditions of the dryer operation depends on various values which characterize the heat transfer. It is according to the research Cho [16], Prvulović [7] and Skuratovsky [10]. The values mentioned by are the heat flux, the area of drying, the temperature differences, etc. In order to determine the effects of heat transfer during convection drying, the topic of heat losses is reviewed as well. On the basis of that, the coefficient of heat transfer has been determined $h_u - h_c$ = 100 $Wm^{-2}K^{-1}$ as a separate value, which shows the share of heat losses through the air outflow from the dryer and the losses due to conduction and radiation through the dryer pipe.

In the beginning of the drying period, the surface of colloid moisture of the material covered by a thin layer of water, has the same feature as free moisture. Owing to the contacts with colloid moisture of the material with heat drying agents the process of liquid evaporation starts. In that case, in the first period of drying, the liquid has accelerated evaporation, taking physically tied moisture into consideration, Figure 5, but in the second period, the rate of drying is visible lower, taking physical-chemistry tied moisture into consideration.

6. CONCLUSION

This work presents the experimental and theoretical research of relevant parameters of drying on the convection pneumatic dryer in food industry. Based on the analysis of energy balance, the heat force of drying has been determined Q_U = 2210 kW, specific consumption of energy q = 3920 $kJkg^{-1}$ of evaporable water, as well as the thermal degree of utilization η_T = 0.74. Energy balance of the dryer can be used to evaluate power condition of the dryer as well as to review the possibility of rational consumption of energy. A significant share of the energy during drying is forwarded to heat transfer 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 energy balance and the results of measuring the temperature of the drying agent, the overall coefficient of the heat transfer is determined in the convection dryer in the amount of h_u = 340 $Wm^{-2}K^{-1}$, and the coefficient of the heat transfer by convection h_c = 240 $Wm^{-2}K^{-1}$. The effects of 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 heat transfer are determined as well as the basic parameters of heat transfer.

For such systems there is very little drying data, allowing the budget, including the heat transfer coefficients. The paper describes the testing of the existing industrial dryer. It was conducted to assess the overall drying operation, installation material and heat balance, determine the speed of drying agents, drying time, energy and other, after construction.

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.

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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 air speed [$kgs^{-1}m^{-2}$]
μ	dynamic viscosity of air [$kgs^{-1}m^{-1}$]
h_u	total heat transfer coefficient [$Wm^{-2}K^{-1}$]
h_c	convection heat transfer coefficient [$Wm^{-2}K^{-1}$]
H	enthalpy [$kJkg^{-1}$]
T_1	air temperature at the inlet of dryer [°C]
T_2	air temperature at the outlet of dryer [°C]
C_p	specific heat capacity [$kJm_n^{-3}K^{-1}$]
W	quantity of evaporated water [kgh^{-1}]
m_1	mass quantities of wet materials [kgh^{-1}]
w	moisture of the dried materijal [%]
ΔT_{sr}	logarithmic mean temperature difference [°C]
Q_U	total quantity of heat [kJh^{-1}]
Q_{conv}	amount of heat transfer by convection [kJh^{-1}]
B	fuel gas consumption [m^3h^{-1}]
H_d	lower gas heat power [kJm^{-3}]
A	drying surface [m^2]
Vk	volume of dryer pneumatic pipe [m^3]
Q_w	amount of heat for evaporation of water [kJh^{-1}]
Q_s	amount of heat for heating the material [kJh^{-1}]
Q_g	heat loss [kJh^{-1}]
η_T	thermal efficiency

ЕКСПЕРИМЕНТАЛНА И НУМЕРИЧКА ИСТРАЖИВАЊА ПРЕНОСА ТОПЛОТЕ И КИНЕТИКЕ СУШЕЊА НА КОНВЕКТИВНОЈ ПНЕУМАТСКОЈ СУШАРИ

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У раду су приказани резултати истраживања који могу корисно послужити при пројектовању и изградњи пнеуматских сушара у прехрамбеној индустрији. Ово се односи на технолошко-техничке карактеристике сушара, енергетске билансе, коефицијенте преноса топлоте и кинетику сушења. Пренос топлоте у овим системима сушења је базиран на принципу директног контакта сушеног материјала и топлог ваздуха. При томе се остварује интензиван пренос топлоте и масе. Експериментална и теоријска истраживања су спроведена на реалном индустријском постројењу конвективне сушаре са пнеуматским транспортом материјала. Нумеричке вредности су дате за оптималне параметре сушења, као и енергетски биланси и модели преноса топлоте.