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EFFECTS OF HEAT TRANSFER IN A HORIZONTAL ROTATING CYLINDER OF THE CONTACT DRYER

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Abstract. *The paper presents a part of the experimental and theoretical research project related to engineering and the application of the contact drying method. It also gives tests of the system parameters of the cylinder dryer with the layer of the dried material, on the surface of the rotating cylinder of the contact dryer in the exploitation conditions. On the basis of the tests, the heat transfer coefficient, heat transfer model, and other process-relevant parameters are determined.*

Key words: *Heat Transfer Model, Contact Dryer*

1. INTRODUCTION

The drying on the contact cylinder dryers is a common diffused technological process in chemical, food-processing and textile industry. These are the devices for drying colloidal solutions, suspensions, viscous fluids, textile materials and the like.

Relatively simple construction and low specific energy consumption make these devices very attractive for applications in the mentioned industries. They also assume only few parameters that can be estimated. Their design needs data about the experimental plants. Both the cylinder dryers and the improvements of the drying technique aim at the efficiency and thrift of these plants, i.e. the reduction of the power and investing costs.

2. THE EXPERIMENTING APPARATUS

The tests are done on the industrial plant of the cylinder dryer, with cylinder diameter d_2=1220 mm and length L=3048 mm, that is heated inside by steam vapor. The scheme

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of the industrial plant is in Fig. 1. When the cylinder is heated and the constant working pressure of p=4bar is released, the necessary experimental measurements in the stationary conditions are done.

The stationary conditions imply the stationeries during a great number of rotations (when nonstationariness that appears in every cylinder rotation separately is excluded). The tests are done under the following conditions:

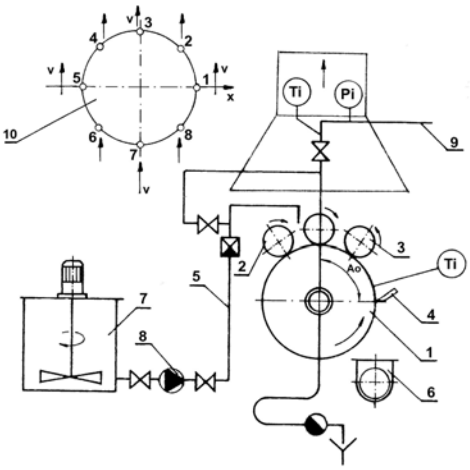

Fig. 1 Technological Scheme of the Cylinder Dryer Plant and the Experimental Apparatus; 1-cylinder; 2-bringing cylinders; 3-scattering cylinder; 4-knife; 5-pipeline for the wet material transporting; 6-the worm conveyer; 7-the reservoir for the suspension preparing; 8-the screw eccentric pump; 9-steam pipeline; 10-the scheme of the measuring places

1) The environment temperature in the closed room, the dry thermometer temperature t=18^{0}C

2) The atmospheric pressure	p_a=1 bar
3) The water vapor pressure	p_p=4 bar
4) The water vapor temperature	t_p=140^{0}C
5) The number of cylinder rotations	n=7.5 min^{-1}
6) The thickness of the dried material moisture	δ_2=0.25 mm
8) The cylinder surface	A=11,5m^2
7) The dried material moisture	
- at the beginning of the drying it was	w_1=65%
- at the ending of the drying it was	w_2=5%
9) Water vapor consumption	m_p=220 (kg/h)

Table 1 gives physical characteristics of the used fluids and material:

Table 1 Physical Characteristics of the Used Fluids and Material at 20 ^{o}C

Media	Density (kg/m^3)	Raising level density (kg/m^3)	Viscosity (m Pa s)	Specific heat (kJ/kgK)
Water	998,2	-	1,01	4,187
Starch	1,164	550	-	-
35% mass solution of starch and water	1,055	-	8,330	3,15

The results of temperature measuring with dried materials layer on cylinder surface are given in Table 2, and the results of measuring of air convection speed in direct vicinity of cylinder, are given in Table 3. The measuring was performed in the plane of cylinder cross-section according to the scheme of experimental points given in Figure 1.

Table 2 Results of Temperature Measurement with Dried Material Layer on the Cylinder Surface t(^{0}C)

Number of measurements points	Distance from cylinder; x=(mm)				
	0	10	20	30	40
1.	89,0	43,5	39,8	37,2	35,0
2.	98,0	40,0	38,0	37,0	35,5
3.	96,0	41,0	39,0	33,0	34,0
4.	81,0	42,0	40,0	31,0	30,0
5.	82,0	35,0	31,0	30,0	29,0
6.	85,0	36,0	28,5	38,0	27,0
7.	83,0	30,0	27,3	26,0	25,0
8.	86,0	38,0	35,0	32,0	30,0
Mean value t (^{0}C)	85,0	37,8	34,2	31,6	30,2

Table 3 The results of Measuring Air Speed with the Layer of Dried Material on the Cylinder Surface v (m/s)

Number of measurements points	Distance from cylinder; x=(mm)				
	0	10	20	30	40
1.	2.				
1.	0,48	0,32	0,28	0,26	0,24
2.	0,48	0,34	0,30	0,28	0,26
3.	0,48	0,38	0,34	0,30	0,28
4.	0,48	0,46	0,38	0,32	0,28
5.	0,48	0,36	0,32	0,28	0,24
6.	0,48	0,45	0,34	0,32	0,28
7.	0,48	0,44	0,36	0,34	0,32
8.	0,48	0,40	0,34	0,30	0,26
Mean value v (m/s)	0,48	0,40	0,33	0,30	0,27

3. METHOD DEFINING COEFFICIENT OF HEAT TRANSFER

The relevant parameter for defining of energetic balance of cylinder dryer presents the coefficient of heat transfer from condensing vapor at cylinder interior onto the surrounding air.

Total heat flux from vapor onto surrounding air can be given in the following form:

$$q_u = h_t\,(t_p - t_v)\ \ [\mathrm{W/m^2}] \tag{1}$$

For big cylinder diameters in relation to envelope thickness, and according the literature [15], we can, with great accuracy, use the term for the coefficient of heat transfer as for flat wall in the equation (2).

So, for example, for cylinder diameter d_2=1220mm and cylinder wall thickness δ_1=35mm, if we define the heat transfer coefficient for flat wall, the mistake is 1.66% in relation to the variable of the heat transfer coefficient for cylinder body. Because of that a simpler form for total coefficient of heat transfer, given by the relation (2) will be applied.

When in the cylinder surface the level of the drying material is raised, the coefficient of heat transfer is defined according to the following equation:

$$\mathrm{h_t} = \frac{1}{\dfrac{1}{\mathrm{h_1}} + \dfrac{\delta_1}{k_1} + \dfrac{\delta_2}{k_{2v}} + \dfrac{1}{h_{2m}}}\ \ [\mathrm{W/m^2K}] \tag{2}$$

Influential parameter on the mechanism of heat transfer is the coefficient of heat transfer (h_m). The value of Nussele's number is defined out of the equation.

$$\mathrm{N_u} = \frac{\mathrm{h_m\,d_2}}{\mathrm{k_v}} = \mathrm{B\,Re^o} \tag{3}$$

On the basis of the grouping influential parameters that are of the greatest influence on the coefficient of heat transfer, the results of experimental and theoretical research are correlated by the form of the equation of Nussele's type [1] :

$$\mathrm{h_m} = \frac{\mathrm{k_v}}{\mathrm{d_2}}\mathrm{B}\left(\frac{\mathrm{d_2G}}{\mu}\right)^{\mathrm{c}} \tag{4}$$

Constants B and C are defined by the method of the least squares.

4. RESULTS OF RESEARCH AND DISCUSSION

By applying the correlation theory to the experimental results of measuring, we have got empirical equations of change of temperature t, in the function of x, distance, from the elevation of cylinder surface at every measuring point.

The temperature curve in the plane of the central cross-section of cylinder with the presentation of standard deviations is given in Figure 2.

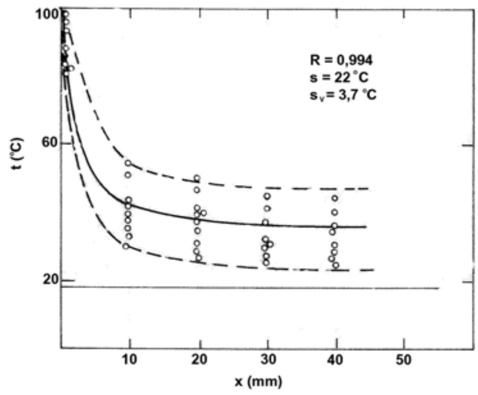

Fig. 2 The Curve of Temperature in the Plane of Central Cross – Section of Cylinder with the Presentation of Standard Deviations

The empiric equation dependence of mean temperature and distance x, from the elevation of cylinder surface has the following form:

$$t_{sr} = 80 - 3{,}80 \cdot x + 0{,}07 \cdot x^2 \tag{5}$$

By applying the correlation theories to the experimental results of measuring we have got empirical equation of speed v, in the distance function x, from the elevation of cylinder surface at every measuring point.

The speed curve of convection in the plane of central cross – section of cylinder with the presentation of standard aberrations, is presented in Fig. 3.

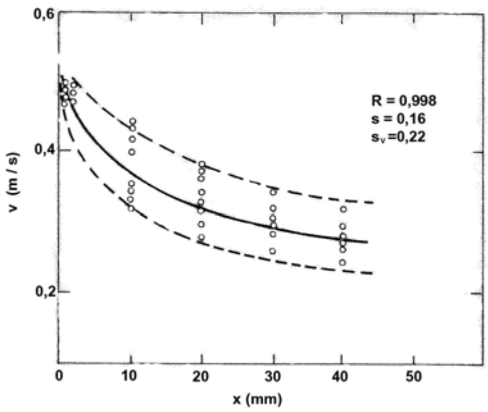

Fig. 3 The curve of Air Convection in the Cylinder Cross-sectional Area with the Presentation of Standard Aberrations

Empirical dependence of mean speed of air v, in direct surroundings of cylinder and distance x, from the elevation of cylinder surface, has the following form:

$$v_{sr} = 0{,}48 - 0{,}009 \cdot x + 10^{-4} x^2 \qquad (6)$$

The research implies that the following parameters are defined, namely: the coefficient of heat transfer from the drying material on surrounding air (h_{2m}) and total coefficient of heat transfer (h_t).

The results of experimental and theoretical research are correlated with correlated equation of Nussele's type, equations (7, 8).

There is also fixed temperature gradient and temperature flux, Figs. (4, 5 and 6).

By applying the correlation theory to the results of experimental and theoretical research projects, we have defined the empirical equation of heat flux dependence and temperature gradient presented with the expression (10).

Figs. 4, and 5 give the results of defining temperature gradient and temperature flux.

It can be noticed that local values of temperature gradient and heat flux have variables along the cylinder size. These variables of given values are formed due to varied air convection in cylinder vicinity, i.e. air mixing and thermo siphon effect of the hood for conducting away heat air and evaporated fluid. So, at certain places (on cylinder surface parts) with a greater air convection speed, higher temperature gradients also appear, Fig. 4.

On the lower"forehead" part of cylinder are higher temperature gradients, taking into account that the air in the room in which the cylinder performs the first conditioning (cooling) of the cylinder"forehead side".

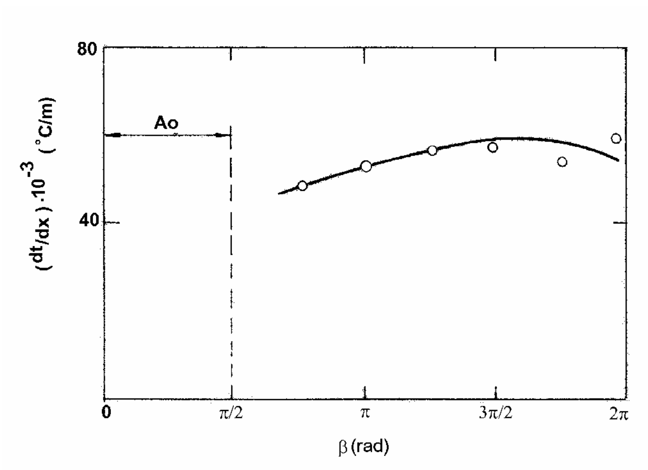

Fig. 4 Change of Temperature Gradient Near Cylinder Surface (d_2= 1.220 mm, t_m=85°C)

Greater variables originate in the lower part (zone) of cylinder, Fig. 5. The dominant effect on the heat flux extent in the given cylinder zone has flux that originates by humidity evaporation from drying material surface. In the given cylinder zone in drying process (the first drying zone) due to the literature [2], intensive humidity evaporation out of drying material appears. Heat flux that originates with evaporating humidity, convection and radiation, presents total heat flux, Fig. 5. There is also fixed temperature gradient and heat flux, Fig.7. So, e.g. the mean value of heat flux in the upper part of cylinder is about 11.000 (W/m^2), while on the lateral side (on the place of the position of the knife for removing dried material) it is 8.000 (W/m^2), Fig. 5.

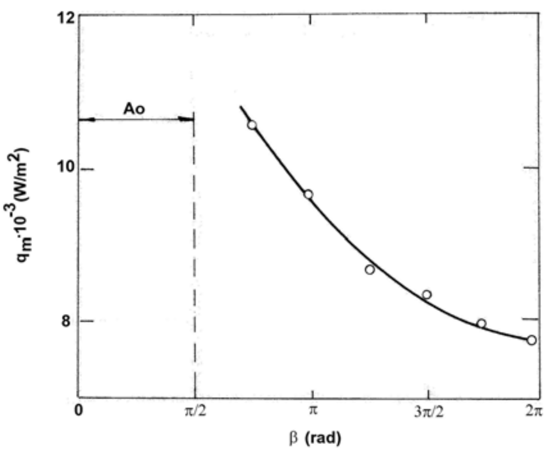

Fig. 5 Heat Flux Change along the Cylinder Size (d_2=1220 mm, t_m = 85^{0}C)

When there is a layer of drying material, total heat flux contains part of flux equal to the produce of heat conductivity of humid material and temperature gradient and flux part equal to the produce of material flux of humidity and specifically humidity enthalpy, i.e. the flux originating with evaporating humidity. Heat flux originating with evaporating humidity by its intensity is a relevant factor in total heat flux when there is drying material on surface.

On the basis of local heat fluxes values, Fig. 5, heat flux has a variable along cylinder size. In the second drying period, and especially in the end of drying, temperature gradient has rising tendency, Fig. 4. Due to research results [2], during drying process at cylinder dryers, humidity remains near the end of drying are taken away at temperature rising on material surface; because of that, there are also higher variables of temperature gradient at the end of drying.

Mean variables of temperature gradient along cylinder size, Fig. 4, are: at the cylinder lower part 57·10^3(^{0}C/m); on the cylinder lateral sides they are 55·10^3(^{0}C/m) and on the top side of cylinder they are 50·10^3(^{0}C/m).

Fig. 6 gives the results of defining temperature gradient in distance function from cylinder surface.

Mean variables of temperature gradient are:

– in the zone at cylinder surface 55,41·10^3(^{0}C/m);

– at the distance of about 5 mm from cylinder surface 6,65·10^3(^{0}C/m)

– at the distance of about 40 mm the cylinder surface 0,0115·10^3(^{0}C/m) etc.

In view of that the change of temperature gradient is the highest at the very cylinder surface, it is in accordance with [3], and [4].

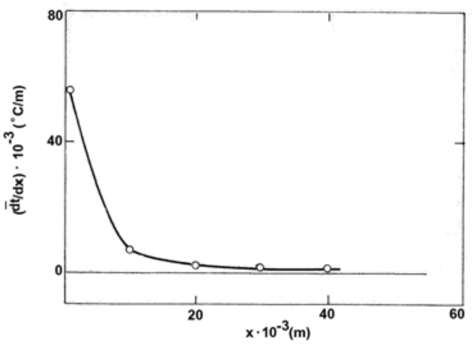

Fig. 6 Mean Variable of Temperature Gradient in Distance Function from the Elevation of Cylinder Surface (d_2=1.220 mm, t_m=85 ^{0}C)

During acting of heating surface of drying material on surroundings in view of heat emitting, temperatures at the surface of the drying material layer are higher than the temperatures at a greater distance of the surface layer of drying material, so that temperature gradients are higher also at the surface layer of drying material, Fig. 6.

We can see two zones of air layer. The first one is in direct vicinity of cylinder surface at the distance of 10 mm. The second zone is distant more than 10 mm, Fig. 6. In the zone of the nearer cylinder surface of temperature gradient is steeper, Fig. 6, it is in accordance with [3] and [5]. These points out higher temperature gradient nearer to the layer surface of drying material.

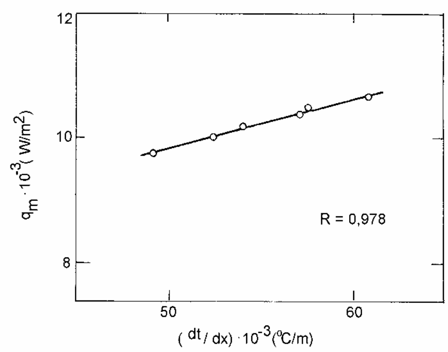

Fig. 7 Dependence of Change Heat Flux, and Temperature Gradient with Cylinder (d_2=1220, t_m=85°C)

Because of poor heat conductivity of air, layers more distant of the cylinder surface, have lower temperature and, along with it, lower temperature gradients than air layer directly near the layer surface of drying material.

Table 4 gives the results of defining heat transfer coefficient by convection (h_m), heat transfer coefficient through radiation (h_r), heat transfer coefficient through evaporating humidity (h_h) and combined heat transfer coefficient (h_{2m}).

Figs. 8, 9 and 10 give research results correlated by the relation of Nussele's and Reynolds's number.

Table 4 Combined heat transfer coefficient (h_{2m}), heat transfer coefficient through convection (h_m), heat transfer coefficient through radiation (h_r) and heat transfer coefficient by evaporating humidity (h_h)

Number of measuring place	Heat transfer coefficient through convection h_m (W/m^{2}K)	Heat transfer coefficient through radiation h_r (W/m^{2}K)	Heat transfer coeff. through evaporating humidity h_h (W/m^{2}K)	Combined coefficient of heat transfer h_{2m} (W/m^{2}K)
1.	2.	3.	4.	5.
4	15,0	7,2	475	497
5	15,8	7,2	335	358
6	17,0	7,1	189	214
7	17,8	7,2	128	153
8	14,7	7,3	87	109
1	16,9	7,1	41	65
Mean value	15,8	7,2	210	233

It is noticed that heat transfer coefficient by convection from drying material layer on (to) air is a variable along cylinder size.

Mean value of heat transfer coefficient is 15,8 (W/m^{2}K). Maximal value of heat transfer coefficient is in lower part zone of cylinder, and it is 17,8 (W/m^{2}K). To greater values of Reynolds's number, Fig. 10, suits as well higher temperature gradient, Fig. 4, and according to it as well greater values of heat transfer through convection and Nussele's number, Figs. 8 and 9.

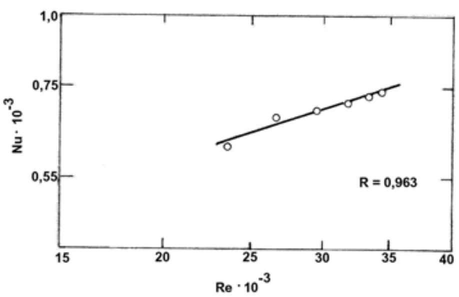

Fig. 8 Dependence of Change of Nussele's and Raynolds's Number with Cylinder (d_2=1220mm, v=0.35m/s, t_m=85^{o}C)

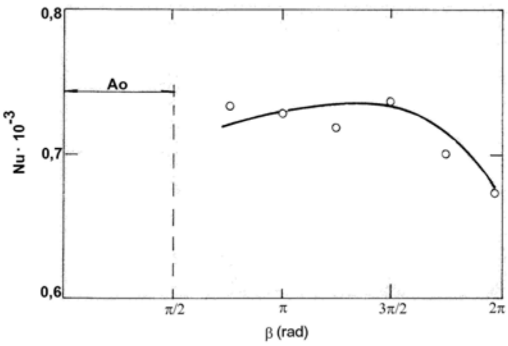

Fig. 9 Nussele's Number Change Along Cylinder Size (d_2=1220mm, v=0.35m/s, t_m=85°C)

On the basis of Reynolds's number value according to Fig. 10, R_e=29.950; what is less than R_{ek}=5 10^5, [6], [7], Convection in direct vicinity of cylinder is laminated.

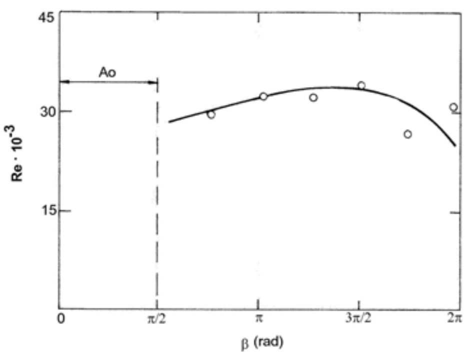

Fig. 10 Change of Reynolds's Number along Cylinder Size (d_2=1220mm, v=0.35m/s)

Changeable speed of air convection in direct vicinity of cylinder effects on change of temperature gradient. Fig. 4 and heat flux, Fig. 5, and what is in accordance with [8], [9]. So local values of temperature gradient and heat flux have variables along cylinder size.

Applying the correlation equation (3) and (4) to the results of experimental and theoretical researches, Fig. 7, we get the following empirical equation:

$$N_u = 0.569 \cdot Re^{0.691} \quad (7)$$

This is Nussele's type equation and it, at the same time, correlates the results of experimental and theoretical researches. Taking into account equation (4), we can define heat transfer coefficient through convection from drying material surface coefficient into surrounding air with the help of the following relation:

$$h_m = 0{,}569\ Re^{0{,}691} \frac{k_v}{d_2}\ [W/m^2K] \tag{8}$$

For equation (7), correlation coefficient is (R=0.863) and standard error of coefficient (c=0.691) is (s=0.05), i.e. 5% and which are defined by the method of the least squares. On the basis of relation (8) and the results of experimental and theoretical research, the empirical equation for thermal resistance of convection heat transfer is defined in the following form:

$$R_{hm} = \frac{d_2}{0{,}569\ Re^{0{,}691}\ k_v}\ [m^2K/W] \tag{9}$$

In Fig. 11, there are results of total coefficient of heat transfer (h_t).

The thermal resistance representative that comprises in itself the combined coefficient of heat transfer ($1/h_{2m}$) has an important effect upon total coefficient of heat transfer (h_t), as can be seen in Table 5.

To greater values of thermal resistance of heat transfer, the lower values of total coefficient of heat transfer are more suitable.

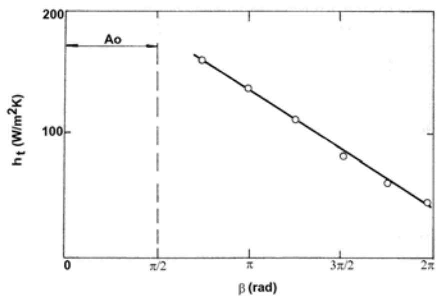

Fig. 11 Change of Heat Transfer Total Coefficient along Cylinder Size (d_2=1220mm, t=85°C)

Table 5 Total Coefficient of Heat Transfer (h_t)

Number of measuring place	Thermal resistance of heat transfer 10^3 (m^2K/W) ($1/h_1 + \delta_1/k_1 + \delta_2/k_{2v} + 1/h_{2m}$)				Total coefficient of heat transfer h_t (W/m^2K)
4	0,1	0,76	3,1	2,0	167
5	0,1	0,76	3,1	2,7	150
6	0,1	0,76	3,1	4,6	117
7	0,1	0,76	3,1	6,5	96
8	0,1	0,76	3,1	9,1	76
1	0,1	0,76	3,1	15,3	52
Mean value	0,1	0,76	3,1	4,3	118

For the mean value for thermal resistance of heat transfer of 0.00826 m^2K/W, the mean value of heat transfer coefficient h_t=118 (W/m^2K) is suitable, Table 5. According to the data from literature [10], heat transfer coefficient amounts (105 - 345) W/m^2K.

Taking into account that local values of combined heat transfer coefficient are (h_{2m}), Table 4, the variables along the cylinder size; they, as a result, give as well changeable technical resistances of heat transfer from the cylinder on air ($1/h_{2m}$). That is also how the changeable values of total heat transfer (h_t) along the cylinder size emerge, Fig. 11.

The dominant effect on changeability of total heat transfer coefficient (h_t), Fig. 11, has the coefficient of heat transfer through evaporating humidity, Table 4. This effect is represented as well in thermal resistance of heat transfer ($1/h_{2m}$). The research results for these dryers include various values of Reynolds's number (which covers air convection speeds from 0.1 to 1m/s) i.e. Re =10000 – 34500, for standard cylinder size of 1220mm.

By applying the correlation theory to the results of experimental and theoretical research, an empirical equation is fixed as the equation for dependence of heat flux and temperature gradient, Fig. 7.

$$q_m = 4750 + 0.1\ \frac{dt}{dx}\ [W/m^2] \qquad (10)$$

The total brought energy of vapor as thermal flux is:

$$q_p = \frac{m_p \cdot r}{A}\ [W/m^2] \qquad (11)$$

The energetic balance is presented in order to check the acquired results. For the mean value of temperature gradient $(dt/dx)10^{-3}$=55 °C/m, Fig. 7, heat flux is q_m=10.250 W/m^2, equation (10). On the basis of equation (1), we get heat flux q_u=10.620 W/m^2. We considered here that the air temperature at the distance from the cylinder x=10 mm, $t_v=t_{sr}$=50 °C, according to equation (5).

The total brought energy of vapor as thermalflux is q_p=11.335 W/m^2, equation (11). The obtained results for the heat flux q_m, and q_u, differentiate for 3,5%, due to the measurement error.

If we compare this with the brought energy of vapor q_p=11.335 W/m^2, we can see that the difference is (715 – 1085) W/m^2. This is, in fact, heat loss. On the basis of that, the thermal degree of the use is η_T = (0,904 – 0,936), i.e. mean value is η_T = 0,92. During the contact drying there is a high degree of heat use due to the direct contact of the drying material layer with the heated surface of the cylinder.

5. CONCLUSION

On the basis of the established experimental results and their analysis, the next conclusion can be drawn:

1. Local values of temperature gradient, heat flux and heat transfer coefficient have variables along the cylinder size, Figs. 4, 5 and 11.

2. Maximal values of heat flux originate in the upper cylinder zone (i.e. in first drying period) according to the literature [2]. The mean value of heat flux in the top zone of the cylinder is about 11.000 W/m^2, and on the lateral cylinder side (at the place of knife position) it is 8.000 W/m^2, Fig. 5.

3. Change of temperature gradient is the greatest at the cylinder surface, Fig. 6. Higher temperature gradients are in the presented cylinder zone, Fig. 4.

4. The values of heat transfer complex coefficient from the surface of drying material on surrounding air, Table 4, give changeable thermal resistances to heat transfer, Table 5. So, originate variables of total heat transfer coefficient along the cylinder size. Here the greatest effect has heat transfer coefficient through evaporating humidity.

5. On the basis of the research results, the mean value of total heat transfer coefficient is h_t=118 (W/m^{2}K), Table 5, and Fig. 11.

6. On the basis of the results of experimental and theoretical research, we have got critical equation (7), of Nussele's type, which correlates to the research results.

The research also included a thermodynamical approach to the problem. There were defined: temperature gradients, heat flux and heat transfer coefficients. In this way, the paper gives a new approach to the drying theory, which has being done during last fifteen to twenty years.

In the final equation system setting is used the access of classical thermodynamics. In this way the problem of presenting potentials of humidity spreading is avoided. The basic parameters are fixed for heat transfer in the process of contact drying, taking into account that various kinds of materials unequally react during drying, as well that characteristics of drying material change dramatically.

The research results can serve:

- for defining essential dependences and parameters of heat transfer with rotating cylinders which are heated inside by vapor
- with designing and developing of new contact cylinder dryings or selecting optimal parameters of heat transfer;
- for technical foreseeing of energetically characteristics of rotating cylinders for cylinder dryers as well for similar drying processes.

The research results have usability because they are based on experimental data taken at the real plant.

In this way, the results of experimental and theoretical research can usefully serve for: researchers, designers and manufacturers of such and similar drying systems, as well for educational purposes.

Total research of relevant parameters of heat transfer has also aimed at a more energy-oriented description of the rotating cylinders for cylinder dryers and drying in order to complement the existing knowledge and explanations of some, so far incompletely explained phenomena in the form of simple devices.

NOMENCLATURE

d_2 – roll diameter, m
n – number of roll rotations, min^{-1}
p – pressure, bar
t – temperature, °C
q – heat flux, W/m^2
x – distance, m
v – speed, m/s

Nu – Nuselts number
Re – Reynolds number
A – the cylinder surface, m^2
G – mass speed stream warm air, $kg/(sm^2)$
μ – dynamic viscosity warm air, kg/(sm)
dt/dx – temperature gradient, K/m (or °C)
w – moisture, %
t_p – is water vapor temperature for cylinder heating (^0C)
t_v – is air temperature of surroundings, (^0C)
r – heat evaporation steam water, (kJ/kg)
h_t – is total coefficient of heat transfer from condensing vapor in cylinder interior on surrounding air, (W/m^2)
k_v – termical conductivity of air, (W/mK)
h_1 – is the coefficient of heat transfer from condensing vapor on cylinder wall, (W/m^2K)
δ_1 – thickness of cylinder envelope, (m)
k_1 – thermo conductivity of cylinder envelope, (W/mK)
δ_2 – mean thickness of drying material layer, (m)
k_{2v} – mean thermo conductivity of material at drying (W/mK)
h_{2m} – heat transfer coefficient from drying material on surrounding air, (W/m^2K)
R_{hm} – thermo resistance of convection heat transfer, (m^2K/W).

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EFEKTI PRENOSA TOPLOTE KOD HORIZONTALNOG ROTACIONOG VALJKA KONTAKTNE SUŠARE

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U radu je prikazano eksperimentalno postrojenje kontaktne valjkaste sušare, koja se koristi za sušenje skrobnih rastvora i suspenzija u prehrambenoj industriji. Eksperimentalna merenja i ispitivanja su izvršena na realnom industrijskom postrojenju valjkaste sušare u procesu proizvodnje.

Izložen je deo eksperimentalnih i teorijskih istraživanja vezanih za tehniku i primenu metode kontaktnog sušenja. Prikazana su ispitivanja i merenja parametara sušenja sa slojem sušenog materijala na površini rotirajućeg cilindra kontaktne sušare u eksploatacionim uslovima. Na osnovu rezultata ispitivanja, određeni su relevantni parametri procesa.

Proračun i dimenzionisanje ovih sušara vrši se po približnoj metodi sastavljanja energetskog bilansa. U okviru ovog rada dat je ekzaktniji pristup rešavanja ovog problema putem termodinamičkog modela. Tako su definisani keoficijenti prenosa toplote, toplotni fluks i modeli prenosa toplote, kod ovako složenog sistema u uslovima rotacije valjka sušare. Na osnovu eksperimentalnih merenja utvrđene su kriterijalne jednačine prenosa toplote i data njihova analiza.

Ključne reči: *model prenosa toplote, kontaktna sušara*