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EXPERIMENTAL AND THEORETICAL INVESTIGATION OF DRYING TECHNOLOGY AND HEAT TRANSFER ON THE CONTACT CYLINDRICAL DRYER

EKSPERIMENTALNA IN TEORETIČNA RAZISKAVA TEHNOLOGIJE SUŠENJA IN PREVAJANJA TOPLOTE NA KONTAKTNEM VALJASTEM SUŠILNIKU

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An experimental and theoretical research on the technology and application of contact drying on the rotating cylinder dryer is presented. Results of measurements of drying parameters of drying starch solution in real working conditions of drying are analysed. Based on tests numerical values of the coefficient of heat transfer, heat transfer model, energy performance, curves of drying kinetics and drying kinetics equations are given, characteristic for drying technology of drying and other relevant parameters of the process.

Keywords: drying technology, heat transfer, contact cylindrical dryers

Predstavljena je eksperimentalna in teoretična raziskava tehnologije in uporabe kontaktnega sušenja na sušilniku z vrtečim se valjem. Analizirani so rezultati meritev parametrov sušenja raztopine škroba v realnih obratovalnih razmerah. Na podlagi numeričnih vrednosti koeficientov prenosa toplote so prikazani model prenosa toplote, poraba energije, krivulje kinetike sušenja in kinetične enačbe sušenja, karakteristične za tehnologijo sušenja in drugi za proces pomembni parametri.

Ključne besede: tehnologija sušenja, prenos toplote, kontaktni valjasti sušilnik

1 INTRODUCTION

Drying on the rollers is a method recognized worldwide as a continuous and very economical technology. Contact roll kiln is applied in several branches of industry, especially in chemical and food industry. It is also applied in drying powdered products in water dispersion with 35–40 % dry matter, colloidal solution and suspension, viscous liquids and pastes.[1] Different dispersions of certain powdered products unequally react by drying, which depends on the properties of the processed powdered material. Thus, it is very difficult to propose a unique technique of cylinder dryer.[2] In comparison to other systems, roller drying accommodation requires less space, service and maintenance are very simple and performed with a small labor force. These advantages, as well as the economical transfer of heat provide a low price of dried final product.

The drying time is in most cases of only a few seconds and it is very important by drying of products sensitive to heat, such as vitamins, which makes better high temperature in short period of time than lower temperatures in long period of time. For substances such as starch solutions in water, contact drying on heated rollers is a good solution of the problem of drying.

Adhesion of dried solution is intensive (in the thin layer) and the drying is done in one incomplete roll revolution. The layer thickness of dried material is regulated by the size of gap between the main and applying rollers, which usually ranges from 0.1–1.0 mm. Thanks to the principle of drying based on direct contact of heated roll and wet material, intensive exchange of heat and mass occurs.

The kiln shown in relation to other technological solutions, has better technical and economic indicators of work. In addition to work efficiency, the essential precondition for any wider application of roll drying is the relatively low specific energy consumption. This consumption by the drying roller is significantly less than by using of other drying mechanisms and spray drying, or in any other way. Generally it is in the range of 1.2–1.6 (kg steam/kg evaporated water). The revolution rate is in the range 5–25 r/min and it depends on the type of dried material. For roll heating used aerated water pressure 3–8 bar, hot water or organic liquids with high boiling temperature are used.[3,4]

The drying efficiency is estimated with the quantity of evaporated moisture, which is in range 10–60 kg h^{-1} m^{-2} depending on the size of the drying cilinder. The relatively simple construction and low specific energy consumption make these drying roll devices very attractive for applications in industry. For these contact roll dryers there are very few technical data on experimental plants which would enable exact calculations necessary for designing of dryers. Drying on cylinder dryers is an improved drying technique. It provides high quality of dried material and high efficiency and economy of plants, i.e. the reduction of the power and investment costs.[5] Descriptions of cylinder dryers and other drying systems are found in references.[6,7]

2 EXPERIMENTAL FACILITY AND RESULTS OF MEASUREMENTS

The tests were performed on the industrial dryer with cylinder diameter d = 1 220 mm and length L = 3 048 mm, heated inside by steam vapor shown in **Figure 1**. By cylinder heating and by constant working pressure of p = 4 bar, the stationary conditions necessary in experimental measurements are obtained for a great number of rotations.

Used measuring instruments:

1) Water vapor pressure
p_p = 4 bar
2) Water vapor temperature
T_p = 140 °C
3) Number of cylinder rotations
n = 7.5 min^{-1}
4) Thickness of cylinder envelope
δ_1 = 35 mm
5) Thickness of the dried material moisture
δ_2 = 0.25 mm
6) Cylinder surface A = 11.5 m^2
7) Water content of dried material
   - start of drying w_1 = 65 %
   - end of drying w_2 = 5 %
8) Water vapor consumption m_p = 268 kg h^{-1}
9) The dried material is 35 % mass solution of potato starch in water.

For experimental measurements, the next measuring instruments and accessories were used:

1) For measuring of water pressure: membrane manometer of 0–10) bar range and precision of 1.6 %;
2) Water temperature: bimetal thermometer with range 0–200 °C and precision of ±2.5 %;
3) Cylinder surface temperature and temperatures in direct vicinity of the cylinder: digital thermometer, type KD-23; with thermo couple NiCr-Ni as sensor, with range –69–199.9 °C and ±0.1 °C precision.
4) Ambient temperature: glass mercury thermometers with range 0–50 °C.
5) Air speed in direct vicinity of the cylinder: anemometer with incandescent wire, type TA 400, Airflow Developments Canada – LTD, with range 0–2) m/s and precision of ±0.02 m s^{-1}.
6) Moisture of drying material: digital meter for humidity, type Metler-LP16 and precision of ±0.1 %.

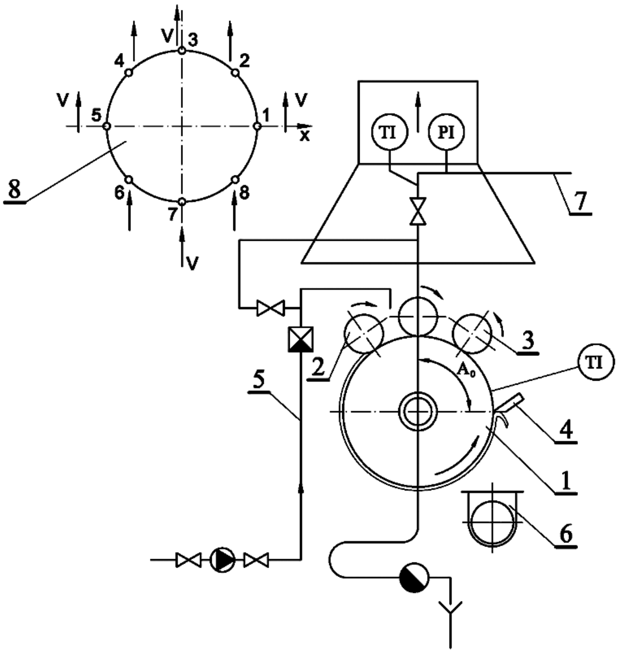

Figure 1: Scheme of experimental contact rool dryer; 1- cylinder; 2- bringing cylinders; 3- scattering cylinder; 4- knife; 5- pipeline for the wet material transporting; 6- worm conveyer; 7- steam pipeline; 8- scheme of measuring points

Slika 1. Shema eksperimentalnega kontaktnega valjastega sušilnika; 1- valj; 2- dovodna valja; 3- razpršilni valj; 4- nož; 5- cevovod za transport sušenega materiala; 6- polžasti prenosnik; 7- parni cevovod; 8- shema merilnih točk

Table 1: Average values of the results of temperature measuring of drying material T_m/°C and content of moisture, w/%

Tabela 1: Povprečne vrednosti izmerjenih temperatur sušenega materiala T_m/°C in vsebnost vlage v masnih deležih, w/%

Measuring place, according to the **Figure 1**	Average values of the temperature dried material, T_m/°C	Moisture of the dried material, w/%	Time drying t/s
3	–	65	0
4	80	54	1
5	81	41	2
6	82	29.5	3
7	84	18.5	4
8	89	10	5
1	96	5	6

Table 2: Results of temperature measuring in drying material layer on the cylinder surface, T/°C

Tabela 2: Povprečne temperature v plasti sušenega materiala na površini valja, T/°C

Number of measurement points	Distance from cylinder; x/m					
	0	0.005	0.01	0.02	0.03	0.04
1.	96	65	43.5	39.8	37.2	35.0
2.	98	59	40	38	37	35.5
3.	–	–	–	–	–	–
4.	80	53	42.0	40.0	31.0	30.0
5.	81	48	35.0	31.0	30.0	29.0
6.	82	45	36.0	28.5	38.0	27.0
7.	84	43	30.0	27.3	26.0	25.0
Mean value T/°C	85.0	50.4	37.8	34.2	31.6	30,2

7) Water power consumption: measurement of condensate mass out of the dryer with the balance "Scalar 100" with the range of 0–100 kg.

The results of temperature measuring with dried materials layer on cylinder surface, and dried material moisture are given in **Table 1**. The measuring was performed in the plane of cylinder cross-section according to experimental points marked in **Figure 1**.

The results of temperature measuring with dried materials layer on cylinder surface are given in **Table 2.**

3 DETERMINATION OF HEAT TRANSFER COEFFICIENT

The overall heat flux from vapor into surrounding air can be calculated as:

$$q_u = U\,(T_p - T) \tag{1}$$

For great cylinder diameters and with relation to envelope thickness, it is possible with great accuracy use the term for the coefficient of heat transfer as for the flat wall the Eq. (2). The difference of heat transfer coefficient for flat wall and for the cylinder diameter d = 1 220 mm and cylinder wall thickness δ_1 = 35 mm is of 1.66 % with regard heat transfer coefficient for cylinder body. Because of simpler form, for calculation of the total coefficient of heat transfer Eq. (2) will be applied[8].

When in the cylinder surface is covered by a layer of drying material, the overall heat transfer coefficient is defined according to equation (2):

$$U = \frac{1}{\frac{l}{h_1} + \frac{\delta_1}{k_1} + \frac{\delta_2}{k_{2m}} + \frac{1}{h_{com}}} \tag{2}$$

The influential parameter of the mechanism of heat transfer is the combined coefficient of heat transfer (h_m), **Table 3** and value of Nussle's number is defined with the equation.

$$Nu = \frac{h_c d}{k_a} = BRe^c \tag{3}$$

On the basis of grouping influential parameters that influence the most coefficient of heat transfer, the results of experimental and theoretical researches are being correlated using the equation of Nussle's type[9–11].

$$h_c = \frac{k_a}{d} B \left(\frac{dG}{\mu} \right)^c \tag{4}$$

The constants (B) and (c), are defined by the method of the least squares.

4 RESULTS AND DISCUSSION

Applying correlation theory on experimental results of measuring empirical equations of drying kinetics were dedeuced.[12,13]

In the initial drying period the dependence of moisture versus drying time is almost linear with initial of drying at t = 0–1) s (**Figure 2**). Thus, in the initial period the drying rate is constant. In the second period of drying in temporal interval t = 1–6 s, the drying dependence changes to a second rank polio. At the end of drying, the content of moisture is of w_2 = 5 %.

In **Figure 3**, the drying rates curves are presented. Initially, the drying rate is constant, and in the second period the drying rate decreases. When the content of moisture is reduced to that of balanced moisture w = 5 %, the evaporation rate is dw/dt = 0.06 (kg water/ kg dried solid).

The presented thermal drying curve in **Figure 4** corresponds to a dependence of polio of second rank. The initial drying temperature is of 80 °C and in the end of drying it is of 96 °C.

Using the method of smallest squares in processing the experiment data the next empiric equations were derived:

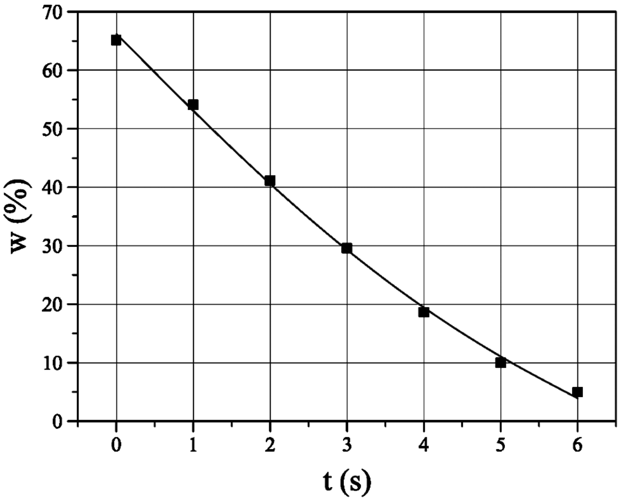

Figure 2: Dependence content of moisture and drying time
Slika 2: Odvisnost vsebnosti vlage od časa sušenja

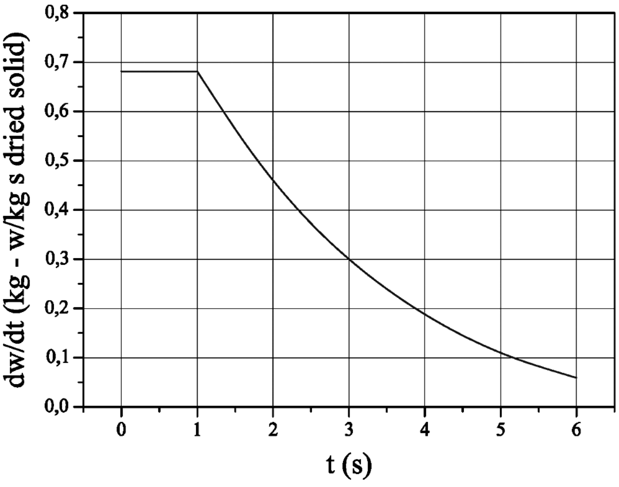

Figure 3: Dependence quantity of dried solid and drying time
Slika 3: Odvisnost količine trdnega materiala od časa sušenja

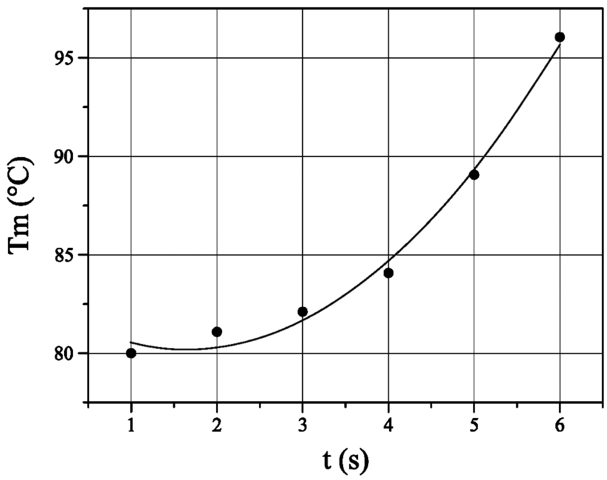

Figure 4: Dependence temperature of drying layer and time
Slika 4: Odvisnost temperature v sušeni plasti od časa sušenja

- dependence content of moisture material and drying time (**Figure 2**):

$$w = 66.166 - 14.196\,t + 0.636\,t^2 \tag{5}$$

- dependence drying rate and drying time (**Figure 3**):

$$\mathrm{d}w/\mathrm{d}t = 0.744 - 0.168\,t + 0.008\,t^2 \tag{6}$$

- drying temperature and drying time (**Figure 4**):

$$T_{\mathrm{m}} = 82.40 - 2.721\,t + 0.821\,t^2 \tag{7}$$

These empiric equations for drying are obtained from experimental data, they define the character of the drying process and are in accord with previous researches.[14,15]

In the initial period of drying, the surface of dried material with high content of moisture is covered by a thin layer of water, it behaves as free moisture and the evaporation is accelerated also with taking up physically tied moisture (**Figure 3**). In the second period, the drying rate is lower, also for tied moisture.

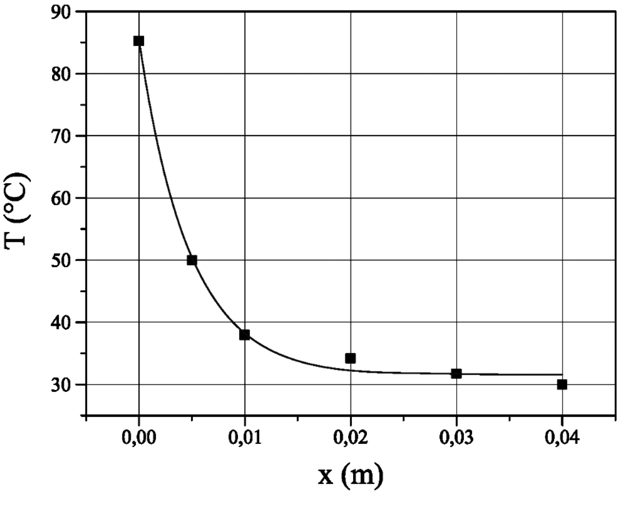

Figure 5: Dependence of temperature in the plane of central cross and distance from cylinder surface
Slika 5: Odvisnost temperature v ravnini srednjega prereza od razdalje do površine valja

Applying the correlation theory for experimental results we obtained empirical equations for change of temperature (T) in function of distance (x), for distance of cylinder surface in every measuring point. The temperature in the plane of the central cross-section of cylinder with consideration of standard deviations is given in **Figure 5**.

The empiric equation for the dependence of mean temperature and distance x (m), from the cylinder surface (**Figure 5**), is:

$$T = 75.50 - 3\,611.88x + 64\,595.87x^2 \tag{8}$$

Based on the results of experimental and theoretical investigation[16,17] the following correlative equations were deduced:

$$N_u = 0.569\,Re^{0.691} \tag{9}$$

$$h_c = 0.569\,Re^{0691}\,(k/d) \tag{10}$$

$$q_m = -\,3.29\,(\mathrm{d}T/\mathrm{d}x)_{x\,=\,0} \tag{11}$$

In the layer of drying material, the total heat flux consists of part of flux equal to the product of heat conductivity of humid material and temperature gradient and of the flux part equal to the product of material flux of humidity, specifically the humidity enthalpy, i.e. the flux originating from evaporation of humidity. The intensity of this flux is a relevant factor in total heat flux by drying the material on the surface.

On the basis of local temperature, the heat flux is variable along the rim of the rotating cylinder. In the second drying period, and especially at the end of drying, the temperature gradient has a rising tendency. During the drying process on cylinder dryers, humidity remnants near the end of drying are evaporated at rising temperature on material surface and cause higher variables of temperature gradient.

Table 3: Combined heat transfer coefficient (h_{com}), heat transfer coefficient with convection (h_{c}), heat transfer coefficient with radiation (h_{r}) and heat transfer coefficient by evaporation of humidity (h_{w})
Tabela 3: Kombinirani koeficient prenosa toplote (h_{com}), koeficient prenosa toplote s konvekcijo (h_{c}), koeficient prenosa toplote s sevanjem (h_{r}) in koeficient prenosa toplote z izparevenjem vlage (h_{w})

Number of measuring place	Convective heat transfer coefficient h_{c} / (W m^{-2} K^{-1})	Radiation heat transfer coefficient h_{r} / (W m^{-2} K^{-1})	Evaporation heat transfer coefficient h_{w} / (W m^{-2}K^{-1})	Combined coefficient of heat transfer h_{com} / (W m^{-2}K^{-1}) = $\mathrm{h_c + h_r + h_w}$
4	15.0	7.0	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

In **Table 3**, are given the results of deduction of heat transfer coefficient with convection (h_c), heat transfer coefficient with radiation (h_r), heat transfer coefficient with evaporation of humidity (h_w) and combined heat transfer coefficient (h_{com}). The heat transfer coefficient with convection from drying material layer in air is variable along the cylinder rim.

The mean value of heat transfer coefficient is 15,8 W m^{-2} K^{-1}. The maximal value of heat transfer coefficient found in the lower zone of cylinder is 17.8 W m^{-2} K^{-1}. To greater values of Reynolds's number, correspond the higher temperature gradient, greater values of heat transfer with convection and higher Nussle's number (**Figure 6**).

The investigated drying process is in reality a natural air streaming around a rotating cilinder with low streaming speed measured at eight measuring points in close aproximity of the cilinde. The air streaming combines natural flux and flux due to the cylinder rotation with rotation rate set for an optimal drying. Since the Raynolds's number depends on air streaming speed, it changes in a given interval, presented on **(Figure 6)**.

According to **Figure 6**, the Reynolds's number is lower than $R_{ek} = 5 \cdot 10^5$ and indicates to a laminar convection in direct vicinity of the cylinder surface.

The thermal resistance consisting of combined coefficients of heat transfer ($1/h_{com}$) has an important effect on the overall heat transfer coefficient (U), as shown in **Table 4**.

The mean value for thermal resistance of heat transfer of $\Sigma R = 8.26 \cdot 10^{-3}$ m^2 K W^{-1} agrees to the mean value of overall heat transfer coefficient U = 118 W m^{-2} K^{-1}, (**Table 4**). According to data from,[18,19] heat transfer coefficient is in the range of 105–345 W m^{-2} K^{-1}.

Taking into account the local values of combined heat transfer coefficients (h_m), (**Table 4**), the variation along the cylinder size indicates to changes of technical resistances of heat transfer from the cylinder to air ($1/h_{com}$) and also originate changes of overall heat transfer coefficient (U) along the cylinder circumference.

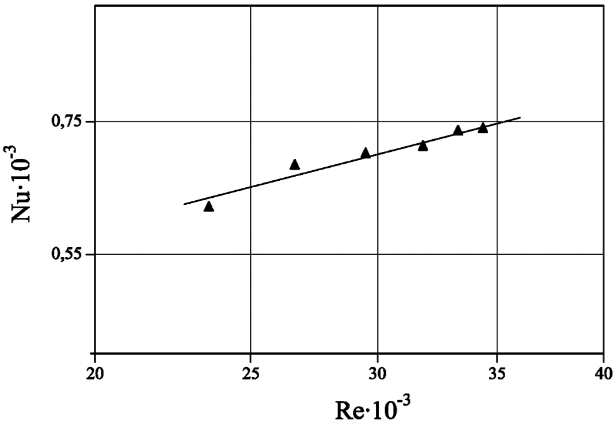

Figure 6: Dependence of change of Nussle's and Raynolds's number with cylinder (d = 1 220 mm, v = 0.35 m/s, T_m = 85 °C)
Slika 6: Odvisnost spremembe Nusslevega in Raynoldsovega števila pri valju (d = 1 220 mm, v = 0.35 m/s, T_m = 85 °C)

Table 4: Overall heat transfer coefficient (U)
Tabela 4. Splošni koeficient prenosa toplote (U)

Measuring point	Thermal resistance of heat transfer 10^3 (m^2 K W^{-1}) $\Sigma R = (1/h_1 + \delta_1/k_1 + \delta_2/k_{2m} + 1/h_{com})$				Overall heat transfer coefficient U/(W m^{-2} K^{-1})
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

The dominant effect on changes of overall heat transfer coefficient (U) is due to changes of coefficients of heat transfer with evaporation of humidity (**Table 4**). This effect is represented as thermal resistance of heat transfer ($1/h_{com}$). The research results for these dryers include various values of Reynolds's number, which cover air convection speeds from 0.1 m/s to 1 m/s i.e. Re = 10000–34500 by standard cylinder size of d = 1 220 mm.

The overall energy of vapour as thermal flux is:

$$q_p = \frac{m_p \cdot r}{A} \qquad (12)$$

The energy balance is presented in order to check the acquired results. For the value of temperature gradient $(dT/dx)_{x=0} = -3\ 611$ Eq. (8), heat flux is q_m = 11 880 W m^{-2}, Eq.(11). The overall energy of vapour as thermal flux is q_p = 13 825 W m^{-2}, Eq. (12).

The difference of both values is 1 945 W m^{-2}, and it is heat loss. Thermal degree of energy use is $\eta_T = 0.859$. During contact drying there is high degree of heat use due to direct contact of drying material layer and the cylinder heated surface.

The evaluation of uncertainty is an ongoing process consuming time and resources. It consists of:

(a) Uncertainty value is from the surface of cylinder temperature and temperatures in direct vicinity of the cylinder and uncertainty of the digital thermometer, type KD-23; and thermo couple NiCr-Ni.
(b) Uncertainty value is from air speed in direct vicinity of the cylinder.

Uncertainty of the anemometer with incandescent wire, type: TA 400, 0–2 m s^{-1}.

Applying the correlation theory to measurement results we have obtained the empirical Eq. (8), (9), (10), (11) with a high coefficient of correlation, equation (8): R = 0.985, eq. (9), (10): R = 0.963, eq. (11): R = 0.978, therefore, the total uncertainty is of 5–7.8 %. The uncertainty analysis of the whole work shows that temperature and air speed measurements have a relatively little influence on the accuracy of results. Thus it is concluded that the obtained results can be used in practice.

5 CONCLUSIONS

On the basis of experimental results and their analysis, the following conclusions are proposed:

- Local values of temperature, heat flux and heat transfer coefficient are different along the cylinder rim;
- maximal values of heat flux originate in the upper cylinder zone (i.e. in initial drying period);
- The values of heat transfer complex coefficient from the surface of drying material on surrounding air produce changes of thermal resistances and heat transfer and cause variations of total heat transfer coefficient along the cylinder rim. The greatest is the effect of heat transfer coefficient with humidity evaporation.
- On the basis of the research results, the mean value of overall heat transfer coefficient U = 118 W m^{-2} K^{-1} was obtained.
- On the basis of experimental and theoretical results the thermo dynamical analysis of the problem was performed and temperature gradients, heat flux and heat transfer coefficients were calculated. In this way, a new approach is given to the drying theory in the last fifteen to twenty years;

The obtained results can be used:

- For defining the essential dependences and parameters of heat transfer with rotating cylinders heated inside by vapor;
- For the design and development of new drying cylinders or selection of optimal parameters of heat transfer.
- The research results can be used because of experimental data taken at real plant as base. For this reason, the results can be useful for: researchers, designers and manufacturers of such and similar drying systems, as well for educative purposes.
- The determined relevant parameters of heat transfer have had as objective a more complete energy description of rotating cylinders for cylinder dryers and drying and to complement the existing knowledge and explanations of some, so far incompletely explained phenomena in simpler devices.

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List of symbols

d/m – roll diameter
n/(r/min) – number of roll rotations
p/bar – pressure
T/°C – temperature
q/(W m^{-2}) – heat flux
x/m – distance
Nu – Nuselts number
Re – Reynolds number
A/m^2 – the cylinder surface
G/(kg s^{-1} m^{-2}) – mass speed stream warm air
μ/(kg s^{-1} m^{-1}) – dynamic viscosity warm air
(dT/dx)/K m^{-1} (or °C m^{-1}) – temperature gradient
w/% – moisture

T_p/°C – water vapor temperature for cylinder heating

r/(kJ kg $^{-1}$) – heat evaporation steam water

U/(W m $^{-2}$ K^{-1}) – overall heat transfer coefficient from condensing vapor in cylinder interior on surrounding air

k_a/(W m^{-1} K^{-1}) – termical conductivity of air

h_1/(W m^{-2} K^{-1}) – coefficient of heat transfer from condensing vapor on cylinder wall

δ_1/m – thickness of cylinder envelope

δ_2/m – mean thickness of drying material layer

k_1/(W m^{-1} K^{-1}) – thermo conductivity of cylinder envelope

k_{2m}/(W m^{-1} K^{-1}) – mean thermo conductivity of material at drying

h_{com}/(W m^{-2} K^{-1}) – combined coefficient of heat transfer

ΣR/(m^2 K W^{-1}) – thermical resistance of heat transfer