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Experimental and Theoretical Study of Energy Characteristics of a Rotating Cylinder

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Preliminary note

The paper presents experimental and theoretical research related to problems of heat transfer in rotating cylinders. Given are the results of measuring the relevant parameters of the rotating cylinder systems in working conditions. The rotating cylinder is heated by steam from the inside. Given a description of the experimental apparatus with the measurement results and methodology. Based on the measurement results, the following values were determined: energy balance, heat transfer coefficients, heat transfer models, as well as other relevant process parameters. Based on the research results obtained in the form of criterial Nusselt type heat transfer equations, as well as other relevant parameters and numerical values.

Eksperimentalna i teorijska studija energetskih karakteristika rotirajućeg valjka

Prethodno priopćenje

U radu su prikazana eksperimentalna i teorijska istraživanja vezana za problematiku prijenosa topline kod rotirajućeg valjka. Prikazani su rezultati mjerenja relevantnih parametara sustava rotirajućeg valjka u radnim uvjetima. Rotirajući valjak se iznutra grije vodenom parom. Prikazan je opis eksperimentalne aparature s rezultatima mjerenja, kao i metodologija rada. Na temelju rezultata mjerenja, ustanovljeni su: energetska bilanca, koeficijenti prijenosa topline, modeli prijenosa topline, kao i drugi relevantni parametri procesa. Na temelju istraživanja dobiveni su rezultati u vidu kriterijalne jednadžbe prijenosa topline Nusseltova tipa, kao i drugi relevantni parametri i numeričke vrijednosti.

1. Introduction

Literature data on heat transfer coefficients in rotating cylinders and other geometric bodies are quite different, probably as a result of different structural characteristics, working conditions and methods of experimental determination of the coefficient of heat transfer, and access to interpretation.

Based on research by [1, 4-5, 9], the total coefficient of heat transfer of static and rotating cylinders in range (25 to 50) W/m^2 K, which is determined on the basis of experimental research .

In literature there are widely accepted conclusions so that by [7, 11-12], heat transfer coefficient variable value which depends on: thick layer cylinder, the type of material, convective characteristics and others.

According to [2, 6, 9], the results of research and knowledge about heat transfer coefficients from static and rotating cylinders, tubes of finite length and other geometrical bodies in the air. From these results we can see that the relevant influential factors in the geometric rotation of the body, the parameters contained in the Nusselt and Reynolds numbers. Upon review of the literature, heat transfer coefficients are very few processed by the rotating body.

2. Experimental apparatus

The tests are done on the rotating cylinder, with the cylinder diameter d_2=1220 mm and the length L=3048 mm, that is heated inside by steam vapor. The cylinder surface A=11.5m^2. The scheme of the industrial plant is on the figure 1. When the cylinder is heated and the constant working pressure of p=4bar, and water vapor temperature t_p=140^{o}C is released. The necessary experimental measurements in the stationary conditions are being done.

Symbols/Oznake

d_2 - cylinder diameter, m
- promjer cilindra

t - temperature, °C
- temparatura

q - heat flux, W/m²
- toplinski tok

x - distance, m
- udaljenost

v - speed, m/s
- brzina

Nu - Nuselts number
- Nuseltov broj

Re - Reynolds number
- Rejnoldsov broj

G - mass speed stream warm air, kg/(sm²)
- masena brzina struja toplog zraka

dt/dx - temperature gradient, K/m (or °C)
- temperaturni gradijent

t_p - temperature water vapor, ^{0}C
- temperatura vodene pare

r - heat evaporation steam water, kJ/kg
- toplina isparavanja vode pare

h_t - total coefficient of heat transfer, W/m²
- ukupni koeficijent prijenosa topline

k_v - termical conductivity of air, W/(mK)
- termička vodljivost zraka

h_1 - the coefficient of heat transfer from condensing vapor on cylinder wall, W/m²K
- koeficijent prijenosa topline kondenzujuće pare na zid cilindra

k_1 - thermo conductivity of cylinder envelope, W/(mK)
- termička vodljivost košuljice cilindra

h_2 -heat transfer coefficient by convection, W/(m²K)
- koeficijent prijelaza topline konvekcijom

hr - heat transfer coefficient by radiation, W/ (m²K)
- koeficijent prijenosa topline zračenjem

R_{h2} - thermo resistance of convection heat transfer, (m²K)/W
- termički otpor konvektivnom prijenosu topline

μ - dynamic viscosity air, kg/(sm)
- dinamička viskoznost zraka

δ_1 - thickness of cylinder envelope, m
- debljina košuljice cilindra

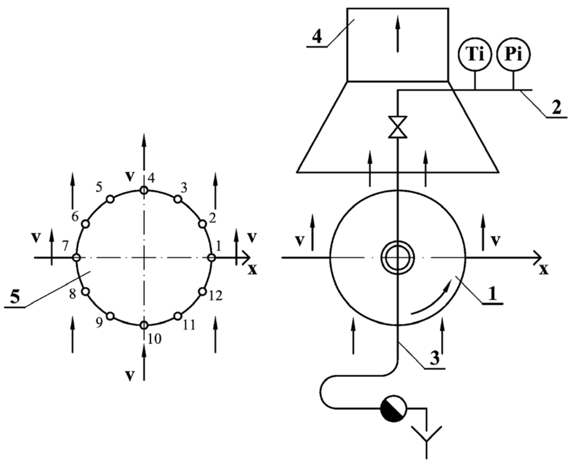

Figure 1. The technological scheme of the experimental apparatus. (1) cylinder, (2) steam pipeline, (3) kondens pipeline, (4) haube, (5) the sheme of the measuring places.

Slika 1. Tehnološka shema eksperimentalne aparature. (1) cilindar, (2) parovod, (3) cijev za kondenzat , (4) hauba, (5) sheme mjernih mjesta.

Under the stationary conditions is meant the stationeries during a great number of rotations (when nonstationariess that appears in every cylinder rotation separately is excluded). The tests are done under the next conditions: Ambient temperature is t_v=18 ^{0}C; The number of cylinder rotations is n=7.5 min^{-1} ; Water vapor consumption m_p=50 (kg/h).

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

3. Material and method

Relevant parameter for defining of energetic balance of cylinder present the coefficient of heat transfer from condensing vapor at cylinder interior onto surrounding air. Total heat flux from vapor onto surrounding air, can be given in the next form:

$$q_u = h_t(t_p - t). \tag{1}$$

For big cylinder diameters in relation to envelope thickness, we can with the great punctuality use the term

Table 1. Results of measurements of temperature t (°C)

Tablica 1. Rezultati mjerenja temperature t (° C)

Serial number of measuring points / Redni broj mjernih mjesta	Distance from cylinder / Udaljenost od cilindra, x (m)								
	0	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040
1	100,2	47,1	44,5	43,0	42,2	41,0	40,0	38,5	37,5
2	96,0	49,2	48,2	48,1	47,8	47,0	46,8	46,0	45,0
3	118,6	55,5	53,3	52,9	52,0	51,0	50,6	49,8	47,0
4	119,0	56,0	54,2	53,5	52,5	51,5	51,0	50,0	47,5
5	125,0	60,0	59,0	58,5	51,5	45,0	44,5	41,0	40,0
6	107,0	50,0	48,0	43,0	40,0	38,0	36,0	33,6	32,0
7	112,6	41,0	40,0	37,0	35,0	34,2	34,0	33,0	31,0
8	118,5	41,8	39,5	37,5	37,2	32,0	29,0	28,5	27,0
9	115,0	37,2	36,0	33,8	32,0	31,0	30,6	29,0	28,0
10	124,5	35,0	34,0	32,1	29,8	28,5	28,0	27,5	26,0
11	107,2	39,0	38,0	37,1	36,2	34,2	34,5	33,0	32,0
12	110,0	43,0	42,1	40,0	38,5	37,0	35,5	34,0	33,0
Mean value / Srednja vrijednost t, °C	110,0	45,3	43,8	42,0	40,2	38,0	37,0	35,6	34,3

Table 2. Results of measurements of air velocity *v* (m/s)

Tablica 2. Rezultati mjerenja brzine zraka *v* (m/s)

Serial number of measuring points / Redni broj mjernih mjesta	Distance from cylinder / Udaljenost od cilindra, x(m)				
	0	0.010	0.020	0.030	0.040
1.	0,48	0,30	0,26	0,20	0,16
2.	0,48	0,32	0,26	0,22	0,20
3.	0,48	0,40	0,30	0,28	0,23
4.	0,48	0,41	0,29	0,27	0,25
5.	0,48	0,42	0,32	0,30	0,28
6.	0,48	0,40	0,36	0,32	0,30
7.	0,48	0,44	0,34	0,30	0,28
8.	0,48	0,43	0,38	0,32	0,30
9.	0,48	0,44	0,37	0,36	0,30
10.	0,48	0,42	0,38	0,32	0,28
11.	0,48	0,40	0,30	0,26	0,22
12.	0,48	0,38	0,32	0,25	0,20
Mean value / Srednja vrijednost *v*, m/s	0,48	0,39	0,32	0,28	0,25

for the coefficient of heat transfer as for flat wall the equation (2).

So, for example, for cylinder diameter d_2 = 1220 mm 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 is raised the level of drying material, the coefficient of heat transfer is defined according to the next equation, [3, 11].

$$h_t = \frac{1}{\frac{1}{h_1} + \frac{\delta_1}{k_1} + \frac{1}{h_c}}. \qquad (2)$$

Influential parameter on the mechanism of heat transfer is the combined coefficient of heat transfer (h_c). Combined heat transfer coefficient includes coefficients of convection (h_2) and radiation. (h_r). The value of Nussele's number is defined out of the equation.

$$N_u = \frac{h_2 d_2}{k_v} = K R_e^{\,a}. \qquad (3)$$

On the basis of grouping influential parameters that at the most influence onto the coefficient of heat transfer, the results of experimental and theoretical researches are being correlated by the form of the equation of Nussele's type [1, 12].

$$h_2 = \frac{k_v}{d_2} K \left(\frac{d_2 \cdot G}{\mu} \right)^a . \tag{4}$$

The constants (K) and (a) are defined by the method of the least squares.

Applying correlation theory on 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 in 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 the Figure 2.

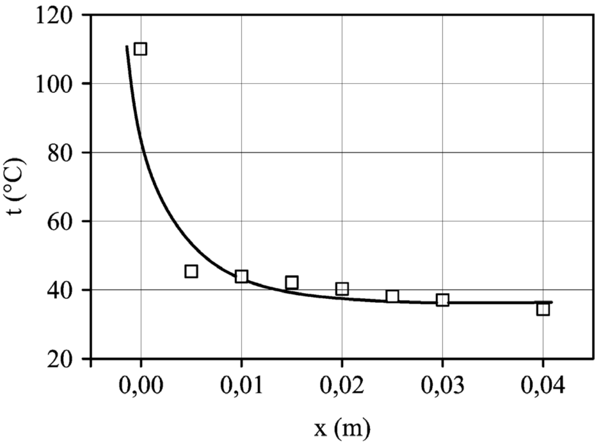

Figure 2. The temperature curve near the central section of the cylinder

Slika 2. Temperaturna krivulja u blizini središnjeg presjeka cilindra

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

$$t = 88{,}829 - 4271{,}995\ x + 77264{,}706\ x^2 \tag{5}$$

Applying correlation theories on experimental results of measuring we have got empirical equation of speed (v), in the distance function (x), from the elevation of cylinder surface in 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 the Figure 3.

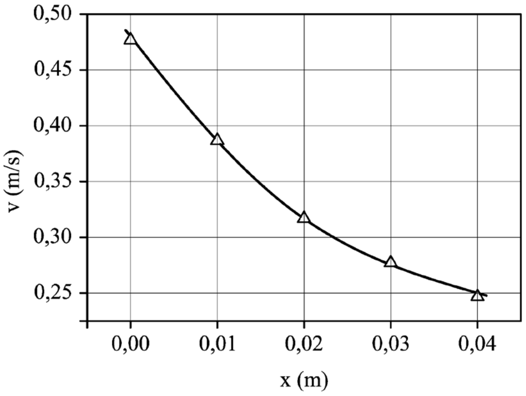

Figure 3. The curve of air velocity near the central section of the cylinder

Slika 3. Krivulja brzine zraka u blizini središnjeg presjeka cilindra

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:

$$v = 0{,}479 - 9{,}985\ x + 107{,}142\ x^2 \tag{6}$$

4. Results and discussion

During such researches are defined: the coefficient of heat transfer by convection (h_2) and total coefficient of heat transfer (h_t). The results of experimental and theoretical researches are correlated with correlated equation of Nussele's type, equations (7, 8).

There is also fixed temperature gradient and heat flux, Figures (4, 5 and 6). 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. So on certain places (on cylinder surface parts) with greater air convection speed, as well appear higher temperature gradients, Figure 4.

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

Greater variables originate in the lower part (zone) of cylinder, Figure 5. The dominant effect on the heat flux extent in the given cylinder zone (π to $3\pi/2$) surface. There is olsou fixed temperature gradient and heat flux, Figure 7. So, e.g. the mean value of heat flux in the upper part of cylinder is about 2.500 (W/m^2), while on the lateral side it 2.000 (W/m^2), Figure 5.

On the basis of local heat fluxes values, Figure 5, heat flux has a variable along cylinder size.

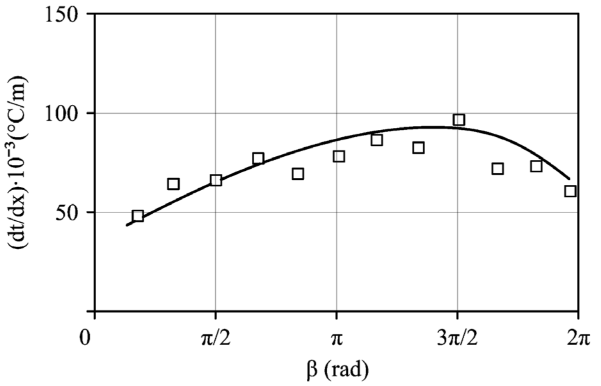

Figure 4. Change of temperature gradient near cylinder surface (d_2 = 1220 mm, t_w = 110 ºC).

Slika 4. Promjena gradijenta temperature blizu površine cilindara (d_2 = 1220 mm, t_w = 110 ºC).

Mean variables of temperature gradient along cylinder size, Figure 4, are: at the cylinder lower part 100 10^3(ºC/m), on the cylinder lateral sides they are 80 10^3(ºC/m) and on the top side of cylinder they are 50 10^3(ºC/m).

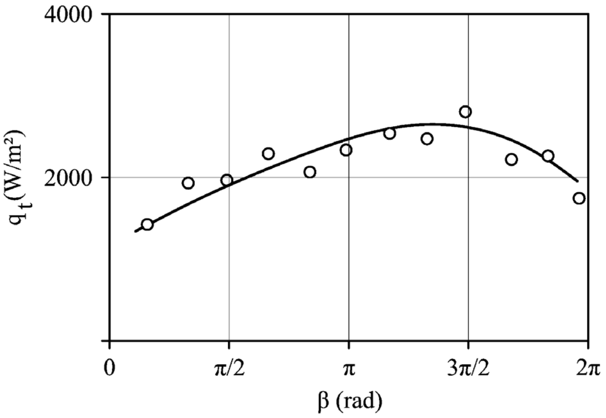

Figure 5. Heat flux change along the cylinder, size (d_2 = 1220 mm, t_w = 85 ºC)

Slika 5. Toplinski tok promjene duž cilindra, veličine (d_2 = 1220 mm, t_w = 85 ºC)

In the Figure 6, are given the results of defining temperature gradient in distance function from cylinder surface.

Mean variables of temperature gradient are:

- in the zone at cylinder surface $74 \cdot 10^3$(ºC/m),
- at the distance of about 5 mm, from cylinder surface $7{,}9 \cdot 10^3$(ºC/m),
- at the distance of about 10 mm the cylinder surface $0{,}85 \cdot 10^3$(ºC/m) etc.

In view of that change of temperature gradient is the highest at the very cylinder surface, and it is in accordance with [5, 9].

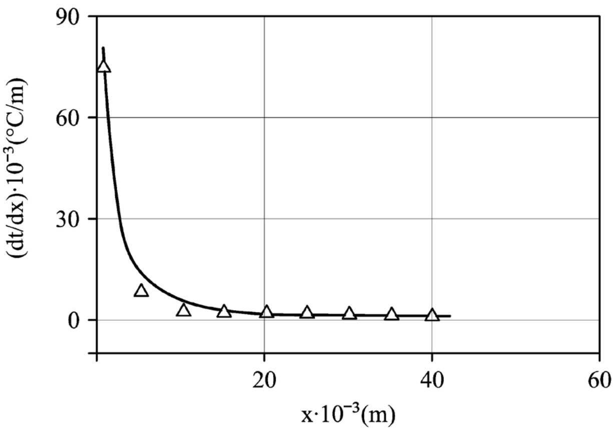

Figure 6. The mean variable of temperature gradient in distance function from the elevation of cylinder surface to (d_2 = 1220 mm, t_w = 110 ºC)

Slika 6. Srednja varijabla gradijenta temperature u funkciji udaljenosti od površine cilindara (d_2 = 1220 mm, t_w = 110 ºC)

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

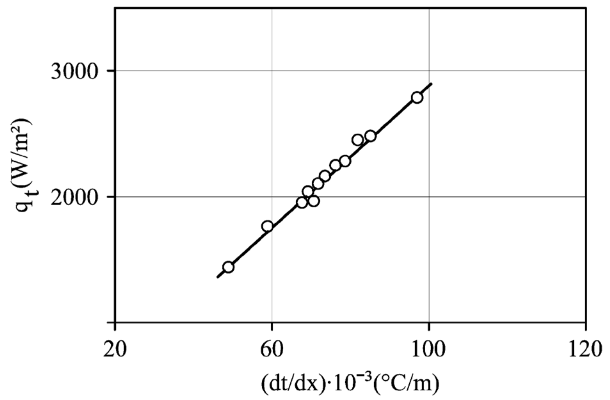

Figure 7. Dependence of change heat flux, and temperature gradient with cylinder to (d_2 = 1220 mm, t_w = 110 ºC, v = 0,34 m/s)

Slika 7. Ovisnost promjene topline i temperaturnog gradijenta za cilindar (d_2 = 1220 mm, t_w = 110 ºC, v = 0,34 m/s)

In the Table 3, are the results of defining heat transfer coefficient by convection (h_2), heat transfer coefficient through radiation (h_r), and combined heat transfer coefficient (h_c).

In the figures 8, 9 and 10, are given the researching results correlated by the relation of Nussele's and Reynolds's number.

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 22,5 (W/m^{2}K). Maximal value of heat transfer coefficient is in lower part zone of cylinder, and it is 26 (W/m^{2}K).

To greater values of Reynolds's number, Figure 10, suits as well higher temperature gradient, Figure 4, and according to it as well greater values of heat transfer through convection and Nussele's number, figure 8 and 9.

Table 3. Combined heat transfer coefficient (h_c), heat transfer coefficient by convection (h_2), heat transfer coefficient by radiation (h_r)

Tablica 3. Kombinirani koeficijent prijelaza topline (h_c), koeficijent prijenosa topline konvekcijom (h_2), koeficijent prijenosa topline zračenjem (h_r)

Number of measuring place / Broj mjernih mjesta	Heat transfer coefficient by convection / Koeficijent prijelaza topline konvekcijom h_2, W/m^{2}K	Heat transfer coefficient by radiation / Koeficijent prijenosa topline zračenjem h_r, W/m^{2}K	Combined coefficient of heat transfer / Kombinirani koeficijent prijenosa topline h_c, W/m^{2}K
1	20,8	7,2	28,0
2	18,2	7,0	25,2
3	19,4	7,8	27,2
4	19,5	7,9	27,3
5	21,0	8,2	29,2
6	22,5	7,4	30,0
7	23,8	7,6	31,4
8	24,7	7,8	32,5
9	25,0	7,7	32,7
10	26,0	8,0	34,0
11	23,5	7,4	31,0
12	23,0	7,5	35,0
Mean value / Srednja vrijednost	22,5	7,5	30,0

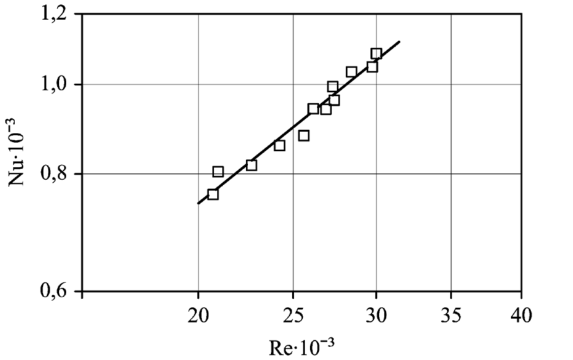

Figure 8. Dependence of change of Nussele's and Raynolds's number with cylinder (d_2 = 1220 mm, v = 0.34 m/s, t_w = 110ºC)

Slika 8. Ovisnost promjene Nuselt i Raynolds broja za cilindar (d_2 = 1220 mm, v = 0.34 m/s, t_w = 110 ºC)

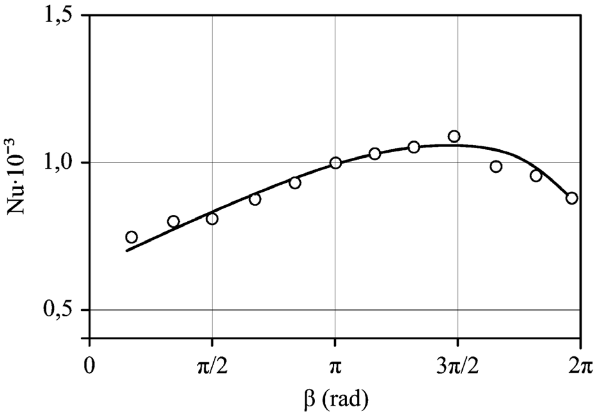

Figure 9. Nussele's number change along cylinder size to (d_2 = 1220 mm, v = 0.34 m/s, t_w = 110 ºC)

Slika 9. Promjena Nuseltovog broja uz cilindar (d_2 = 1220 mm, v = 0.34 m/s, t_w = 110 ºC)

On the basis of Reynolds's number value according to the figure 10, R_e=28.750; what is less than R_{ek}=5 10^5, [6]. Convection in direct vicinity of cylinder is laminated.

Changeable speed of air convection in direct vicinity of cylinder effects on change of temperature gradient.

Figure 4 and heat flux, Figure 5, and what is in accordance with [4, 8].

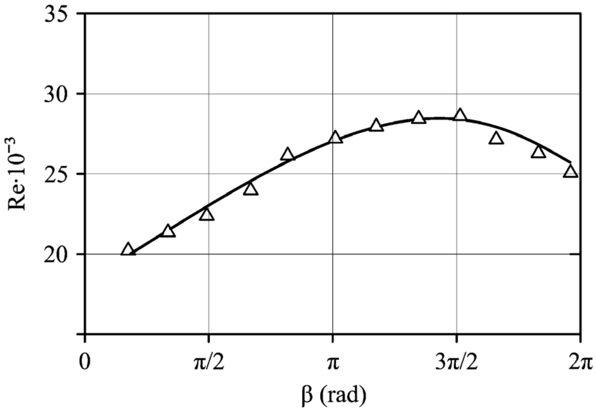

Figure 10. The change of Reynolds's number along cylinder size (d_2 = 1220 mm, v = 0.34 m/s)

Slika 10. Promjena Rejnoldsovog broja uz cilindar (d_2 = 1220 mm, v = 0.34 m/s)

So local values of temperature gradient and heat flux have variables along cylinder size.

Applying the correlation equation (3) and (4) on the results of experimental and theoretical researches, Figure 8, we get the next empirical equation:

$$N_u = 0.0392 R_e^{0.993}. \quad (7)$$

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

$$h_2 = 0.0392 R_e^{0.993} \frac{k_v}{d_2}. \qquad (8)$$

On the basis of the relation (8) and the results of experimental and theoretical researches, was defined the empirical equation for thermical resistance of convection heat transfer in the next form:

$$R_{h2} = \frac{d_2}{0.0392 R_e^{0.993} k_v}. \qquad (9)$$

In the Figure 11, are given the results of total coefficient of heat transfer (h_t).

The thermical resistance representative that consists in itself the combined coefficient of heat transfer ($1/h_c$) has important effect upon total coefficient of heat transfer (h_t), what we can se in the Table 4.

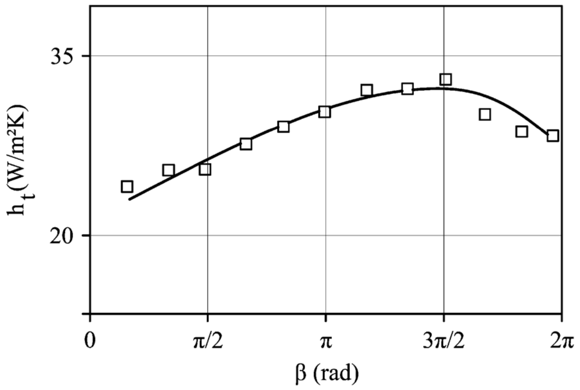

Figure 11. The change of heat transfer total coefficient along cylinder size to (d_2 = 1220 mm, t_w = 110 °C)

Slika 11. Promjena ukupnog koeficijenta prijanosa topline uz cilindar veličine (d_2 = 1220 mm, t_w = 110 °C)

To greater values of thermical resistance of heat transfer suit lower values of total coefficient of heat transfer.

To the mean value for thermical resistance of heat transfer of 0.03416 m²K/W suits the mean value of heat transfer coefficient h_t=30 W/m²K, the table 4. According to the data from literature [7], [10], heat transfer coefficient amounts (25 -50) W/m²K.

Taking into account that local values of combined heat transfer coefficient are (h_c), the table 4, the variables along the cylinder size; they as result give as well changeable technical resistances of heat transfer from the cylinder on air ($1/h_c$). So originate also changeable values of total heat transfer (h_t) along the cylinder size, the Figure 11.

Table 4. The total coefficient of heat transfer (h_t)

Tablica 4. Ukupni koeficijent prijenosa topline (h_t)

Number of measuring place / Broj mjernih mjesta	Thermical resistance of heat transfer / Toplinski otpor prijenosa 10^3 m²K/W $[(1/h_1 + \delta_1/k_1) + (1/h_c)]$			Total coefficient of heat transfer / Ukupni koeficijent prijenosa topline h_t, W/m²K
1	0,1	0,76	35,7	27,3
2	0,1	0,76	39,7	24,6
3	0,1	0,76	36,8	26,5
4	0,1	0,76	36,6	37,5
5	0,1	0,76	34,2	35,0
6	0,1	0,76	33,3	29,3
7	0,1	0,76	31,8	30,6
8	0,1	0,76	30,7	31.7
9	0,1	0,76	30,6	31,8
10	0,1	0,76	29,4	33,0
11	0,1	0,76	32,3	30,2
12	0,1	0,76	32,8	29,7
Mean value / Srednja vrijednost	0,1	0,76	33,3	30,0

The dominant effect on changeability of total heat transfer coefficient (h_t), Figure 11, has the coefficient of heat transfer convection (h_2), the Table 3. This effect is represented as well in thermical resistance of heat transfer ($1/h_c$). The research results for these dryers include various values of Reynolds's number (which covers air convection speeds from (0.25 to 0.48m/s) i.e. Re =20.000 – 30.000, for standard cylinder size of 1220 mm.

Applying correlation theory on the results of experimental and theoretical researches, an empirical equation is fixed the equation for dependence of heat flux and temperature gradient, Figure 7.

The total brought energy of vapour as thermalflux is:

$$q_p = \frac{m_p r}{A}. \qquad (10)$$

The energetic balance is presented in order to check the acquired results. For the mean value of temperature gradient $(dt/dx)10^{-3}$=85 °C/m, Figure 4, heat flux is q_t=2504 W/m², figure 5. On the basis of the equation (1), we get heat flux q_u=2580 W/m². We considered here that the air temperature at the distance from the cylinder x=0,01 m, t = 54 °C, according to the equation (5). The total brought energy of vapour as thermalflux is q_p=2576 W/m², equation (10). The received results for the heat flux q_t, and q_u, end q_p, differentiate for 3%, due to the measurement error.

5. Conclusion

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

- Local values of temperature gradient, heat flux and heat transfer coefficient have variables along the cylinder size, Figures 4, 5 and 11.
- Maximal values of heat flux originate in the upper cylinder zone according to the literature [2, 11]. The value of heat flux in the top zone of the cylinder is about 2.500 W/m^2, and on the lateral cylinder side it is 2.000 W/m^2, Figure 5.
- Change of temperature gradient is the greatest at cylinder surface, Figure 6. Higher temperature gradients are in the presented cylinder zone, Figure 4.
- The values of heat transfer complex coefficient from the surface of cylinder on surrounding air, the Table 3, give changeable thermical resistances to heat transfer, the Table 4. So, originate variables of total heat transfer coefficient along the cylinder size. Here the greatest effect has coefficient heat transfer convection (h_2).
- On the basis of the research results, the mean value of total heat transfer coefficient is h_t=30 (W/m^{2}K), the Table 4, and the Figure 11.
- On the basis of the results of experimental and theoretical researches, we have got the critical equation (7), of Nussele's type, which correlates the research results.

In the scope of the research was applied thermodynamically access to the problem. There were defined: temperature gradients, heat flux and heat transfer coefficients. In final equation system setting was used the access of classical thermodynamics. The researcher results can serve:

- for defining essential dependences and parameters of heat transfer with rotating cylinders which are heated inside by vapor;
- for technical foreseeing of energetically characteristics of rotating cylinders as well for similar processes.

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

Total researches of relevant parameters of heat transfer have had as objective as well more complete energetically describing rotating cylinders in order to complement the existing knowledge and explanations of some, so far incompletely explained phenomena in appearance simple devices.

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