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WŁODZIMIERZ KAWKA *, *MARIUSZ RECZULSKI* **

THE OPTIMALIZATION OF HEATING STEAM PRESSURE ON THERMAL EFFECTIVENESS OF DRYING CYLINDERS

The study presented here offers an analysis of the heat flow through the wall of the Yankee cylinder when regarded as a thin-walled vessel. The effect of the selected design and process parameters (i.e. cylinder diameter and steam pressure) on density of the heating stream has been analyzed and discussed for both cast iron and steel cylinders. Based on the work presented here, the optimal ranges for steam pressure have been derived and proposed for cylinders mounted at various locations within the drying section.

Up to recently, maintaining drying capacity even for the fastest papermaking machines required designers of the drying section to increase the number of the drying cylinders directly proportionally to the intended speed of the papermaking machine. However, the latest trend for the drying section to keep up its drying capacity with the increased machine speed is to increase the drying effectiveness of the existing cylinders rather than adding new units.

Main innovations driving higher drying effectiveness of the drying sections are:

– introduction of the open felts, with a high air and vapor permeability, that allow for a more effective removal of the water and vapor outside the immediate space taken by the drying cylinders,

– optimization of heat management around drying cylinders with addition of the closed cylinder hoods and the use of high intensity and high temperature forced air blowing directly on the surface of the paper being dried, in

* *Technical University of Lodz, Institute of Papermaking and Printing, 223 Wólczańska St., 90-924 Lodz, Poland, e-mail: wlkawka@p.lodz.pl*

** *Technical University of Lodz, Institute of Papermaking and Printing, 223 Wólczańska St., 90-924 Lodz, Poland, e-mail: mariusz.reczulski@p.lodz.pl*

effect replacing the standard contact-type drying with a more effective mix of contact and convection drying technology,
– optimization of ventilation/air management inside a drying section through introduction of the hot-air blow rolls, i.e. Madeleine or similar, that ventilates pockets created between paper web and surface of the drying cylinders,
– introduction of the more effective de-airing of the steam delivery system and optimized de- watering of the drying cylinders,
– introduction of the chemical additives to heating steam to promote a faster dropwise condensation inside cylinders, [1, 2, 3].

Drying effectiveness can also be improved by increasing pressure of the heating steam resulting in an increased temperature gradient between steam and the paper web that in turn increases amount of heat being delivered to the paper being dried [4].

For the newer designs of the papermaking machines for special - purpose papers like carton and bag paper, pressure of the heating steam inside the cylinders can be even as high as 8 bar ($8x10^5$ N/m^2) or higher. According to published studies [5, 6, 7, 8] changing heating steam pressure from 2 to 8 bar can result in up to 80% increase in the actual amount of heat being delivered to the paper web inside the drying section.

However, the effect of increased steam pressure on the drying section effectiveness seems have its limitations. When pressure of the heating steam is increased over a certain optimum level, the necessary increase in the thickness of the walls of the drying cylinders effectively constrains the amount of heat being delivered to the paper web being dried.

The above limitation is the main subject being discussed in the subsequent paragraphs for a Yankee cylinder.

Heat transfer through the wall of the drying cylinder

The Yankee cylinder, a drying cylinder with a large diameter, can be treated as a thin-walled device. Simplified model of the heat transfer from the heating steam inside the cylinder to paper web is illustrated in Figure 1.

This simplified heat transfer model is based on the following assumptions:
– cylinder wall can be treated as a flat plane, which results in a linear temperature gradient within the wall,
– temperature of the paper web is constant throughout its thickness,
– the overall cylinder wall-to-paper web heat transfer coefficient includes the heat transfer through the thin air layer between cylinder wall and paper web and inside the paper web itself.

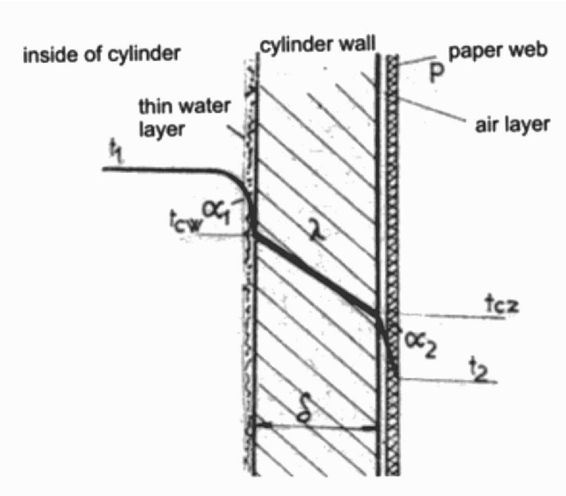

Fig. 1. Model of the heat transfer through the cylinder wall

Based on the above assumptions, the general relation for the heat transfer through one square meter of cylinder surface can be described as:

$$q = \left(\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}\right)^{-1} (t_1 - t_2) \tag{1}$$

where:

q – density of the heat stream

t_1 – temperature of the heating steam inside the cylinder

t_2 – paper web temperature

α_1 – coefficient for steam-to-cylinder wall heat transfer

δ – cylinder wall thickness

λ – heat transfer coefficient for cylinder wall

α_2 – coefficient for outer cylinder wall-to-paper web heat transfer.

The coefficient for steam-to-cylinder wall heat transfer a_1 can be described as:

$$\alpha_1 = \frac{\lambda_w \left(\frac{\partial t_c}{\partial R}\right)_{R=R_w}}{t_1 - t_{cw}} \tag{2}$$

where:

t_{cw} – temperature of the inner surface of the cylinder wall

λ_w – coefficient of heat transfer through a thin water layer on the inner surface of the cylinder wall

The value of the $\left(\frac{\partial t_c}{\partial R}\right)_{R=R_w}$ term usually ranges from 200 to 600 deg/m (deg is a new SI unit replacing commonly used °C for describing a temperature gradient, i.e. °C/m).

The coefficient α_1 encompasses all constrains for the heat transfer from the heating steam to the cylinder wall, including resistance to heat flow through the thin water layer on the inner surface of the cylinder wall. However, the magnitude of heat conductivity through the thin water layer alone, described here as λ_w, renders other restrains to heat transfer as negligible.

Therefore, the coefficient α_1 depends, to a large extent, on the distribution of the thin water layer on the inner surface of the cylinder wall, and thus on the cylinder rotational speed. With that in mind, we can state that the effectiveness of the process to extract condensation from the cylinder has a very significant impact on this variable, with a degree of the heating steam aeration having also a significant but a somewhat lesser effect.

According to Zürn [9] α_1=1860 W/(m^{2}K), however, for a similar example, Schädler [10] assumed α_1= 4070 W/(m^{2}K), in an analytical discussion of that study. Furthermore, Michiejew [10] stated that the value of this coefficient ranges from 4650 to 17450 W/(m^{2}K).

The values suggested by Zürn and Schädler appear to be justified by the thick layer of condensation on the inner surface of the cylinder wall when compared to other types of heating matter.

The coefficient for heat transfer from outer surface of the cylinder wall to the paper web, described here as α_2, can be described as:

$$\alpha_2 = \frac{\lambda_p \left(\frac{\partial t_c}{\partial R}\right)_{R=R_z}}{t_{cz} - t_2} \tag{3}$$

where:

t_{cz} – temperature of the outer surface of the cylinder wall

t_2 – temperature of the outer surface of the paper web

λ_p – heat transfer coefficient for paper web

The magnitude of the coefficient α_2 depends, to a large extent, on a direct contact area between paper web and cylinder wall, and thus on the thickness of air layer between paper and cylinder, with paper caliper and degree of dryness also being significant but somewhat lesser contributors. Furthermore, the value of the coefficient α_2 varies in time as dryness of the paper web progressively changes from the moment of the first contact between paper and cylinder all the way to the moment the paper web is separated from the cylinder.

For simplification, it was assumed in this study that coefficient α_2 remains constant for the entire time paper web stays in contact with a drying cylinder; the average value of this coefficient has been used in subsequent analytical discussion. According to Zürn [9] α_2=1860 W/(m^{2}K). However, results from the study by Schädler [10] point to a more variable value of this coefficient which changes with paper dryness from appx. 810 W/(m^{2}K) in the initial phase of the drying process down to appx. 230 W/(m^{2}K) in the final phase of the drying process. On average, for a yankee cylinder located in the middle of the drying section, value of this coefficient is about 580 W/(m^{2}K).

For safety reasons, the minimum thickness of the cylinder wall, treated as a pressure vessel, is usually set by the appropriate national office in charge of a safety assurance for technical devices and according to the Polish Office of Technical Assurance (Urząd Dozoru Technicznego) can be described as:

$$\delta = \frac{p \cdot D \cdot (1 + c)}{\frac{2,3}{a} \cdot k_r \cdot z + p} \qquad [m] \tag{4}$$

where:

p – pressure (computational) of the heating steam inside the cylinder [bar]

D – outside cylinder diameter [m]

k_r – minimum acceptable burst strain:

200 to 300 kG/cm^2 (20 to 30 MN/m^2) for cast iron

600 kG/cm^2 (60 MN/m^2) for steel

z – calculated coefficient of machine direction tensile strength for rolling milled elements; z=1 for cast cylinders, z=0.6 to 0.9 for welded cylinders, depends on the welded joints construction

a – coefficient describing relation between outer and inner diameter of the cylinder; a=1 is a commonly accepted value for yankee cylinders

c – safety margin for wall thickness, i.e. additional thickness of the cylinder wall needed to account for mechanical and chemical related deteriorations and wear of the wall material over the working live of the cylinder; c=0.1 is a commonly assumed value

The heat transfer coefficient for cylinder walls has a fairly constant value that can change a little in response to a large change in temperature level. With a commonly used temperature range for typical drying cylinders, the value of this coefficient is constant and is equal to approx. λ= 45 W/(mK).

When relationships 2, 3 and 4 are applied to equation 1, with k_r=270 kg/cm for cast iron, k_r=600 kg/cm^2 for steel and z=0.75 the density of the heating stream can be described as:

– for cast iron cylinders:

$$q = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{\frac{p \cdot D \cdot (1+c)}{\frac{2,3}{a} \cdot k_r \cdot z + p}}{\lambda}} (t_1 - t_2) \qquad [\mathrm{W/m^2}] \qquad (5)$$

$$q = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{D}{\frac{17000}{p} + 36,4}} (t_1 - t_2) \qquad [\mathrm{W/m^2}] \qquad (6)$$

– for steel cylinders:

$$q = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{\frac{p \cdot D \cdot (1+c)}{\frac{2,3}{a} \cdot k_r \cdot z + p}}{\lambda}} (t_1 - t_2) \qquad [\mathrm{W/m^2}] \qquad (7)$$

$$q = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{D}{\frac{37700}{p} + 36,4}} (t_1 - t_2) \qquad [\mathrm{W/m^2}] \qquad (8)$$

where:

t_1 – temperature of the heating steam inside the cylinder, °C
t_2 – paper web temperature, °C
α_1 – coefficient for steam-to-cylinder wall heat transfer, W/(m^{2}K)
α_2 – coefficient for outer cylinder wall-to-paper web heat transfer, W/(m^{2}K)
p – pressure of the steam inside cylinder, bar
D – cylinder diameter, m

Assuming that the sum of constant values $\frac{1}{\alpha_1} + \frac{1}{\alpha_2} = 0.00108(\mathrm{m^2K})/\mathrm{W}$, paper temperature t_2= 120 °C and steam temperature t_1 dependence on steam pressure p described by following equation:

$$t_1 = 100(p + 1)^n \quad \text{where} \quad n = 0.253 \qquad (9)$$

we can express the density of the heat flux q as a function of both cylinder diameter D and steam pressure p:

$$q = f(p, D) \qquad (10)$$

Figure 2 shows a family of curves described by the function (10) with a linear change in the cylinder wall thickness δ.

The relations shown in Figure 2 clearly indicate that the density of the heat flux q reaches a maximum for each individual cylinder diameter D, with this maximum moving towards lower pressures with an increase in diameter.

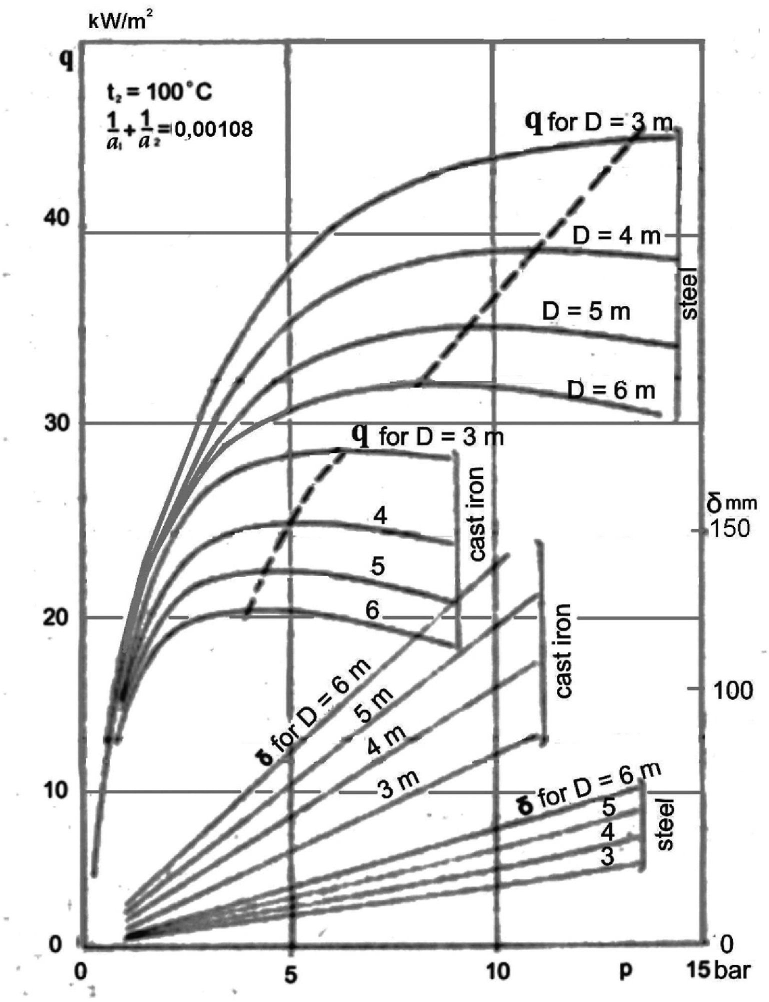

Fig. 2. Effect of cylinder diameter and steam pressure on density of the heating stream for cast iron and steel cylinders: D – cylinder diameter, t_2 – paper temperature, q – heat flux

As mentioned before, the actual temperature of the paper varies during the drying process. It depends on variables like temperature of the cylinder, temperature of the immediate surrounding, degree of the paper wetness, as well as type of drying felt or air management around moving paper web.

During removal of the free water (water not bound inside fiber), temperature of air around paper web cannot exceed 100°C, in this case it ranges from 80 to 90°C. Temperatures higher than 100°C can be achieved only when paper wetness is lower than a critical wetness within its hygroscopic range.

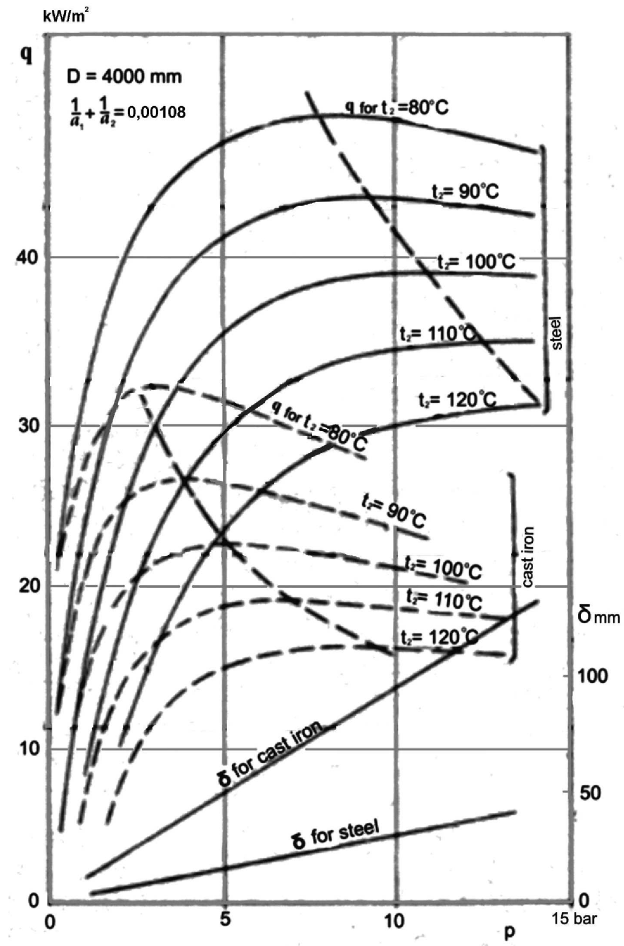

Fig. 3. Effect of paper temperature and steam pressure on density of the heating stream for cast iron and steel cylinders: p – steam pressure, t_2 – paper temperature, q – heat flux

Assuming cylinder diameter D=4000 mm and $\frac{1}{\alpha_1}+\frac{1}{\alpha_2} = 0.00108$ (m^{2}K)/W, we can describe density of the heating stream as a function of steam pressure and paper temperature, as shown in Figure 3:

$$q = f(p, t_2) \tag{11}$$

The data shown in Figure 3 indicate that lower paper temperatures result in the maximum moving towards lower steam pressures, while also causing an increase in density of the heat flux. Modern designs of the drying sections, with an intensive airflow management around paper web, allow for a lower paper temperature with a more intense heat transfer, this in turn leads to higher water evaporations per square meter of the cylinder surface. Therefore, compared to a typical contact drying, combination of the closed hood drying systems with forced air paper drying allows for a lower steam pressure for Yankee cylinders.

Figure 4 shows the effect of heat transfer coefficients α_1 and α_2 on density of the heating stream as a function of both those parameters and steam pressure:

$$q = f(p, \alpha_1, \alpha_2) \tag{12}$$

Again, the data in Figure 4 indicate that, with a decrease in value of either one of those coefficients, or both of them, the maximum moves towards higher steam pressures while density of the heat stream is seen to decrease, which seems to be justified.

To improve the overall heat transfer from the heating steam inside the drying cylinder to the paper web, and thus to improve the overall drying effectiveness, it is important to maximize heat transfer coefficients on both sides of the cylinder wall by eliminating condensation layer on the inner surface of the cylinder wall while maximizing a direct contact area between paper and cylinder (i.e. eliminating the air packets between paper web and cylinder surface).

Zürn [9] offers a somewhat different approach to this problem, where a non-dimensional parameter describing density of the heating stream flowing through the cylinder surface is derived from relations 1 and 4 (in their German form). Based on his analysis, he is able to find maxima for functions10, 11 and 12 for a specific case of D=5 m and $\alpha_1 = \alpha_2$=1860 W/(m^{2}K). The optimal density of the heating stream for this particular case is reported to be achieved at steam pressure of 5.4 bar in the case of a cast iron cylinder.

Based on the above assumptions, the values for heat flux, shown in Figures 2 to 4, can be derived for a varying thickness of the cylinder wall that, in each case, is a function of the cylinder diameter and steam pressure.

To demonstrate changes in heat flux for a real-life cylinder with a constant wall thickness, the values of this variable have been calculated as a function of steam pressure only.

The results from this analysis are illustrated in Figure 4 as dashed lines a, b and c for a cylinder with a 4000 mm diameter and a required wall thickness for the working steam pressure of 5 bar at three different levels of heat transfer resistance (first term in equation 1). Examination of these curves indicates a significant drop in heat flux in response to a pressure drop of the heating steam. With a relatively negligible level of resistance to heat

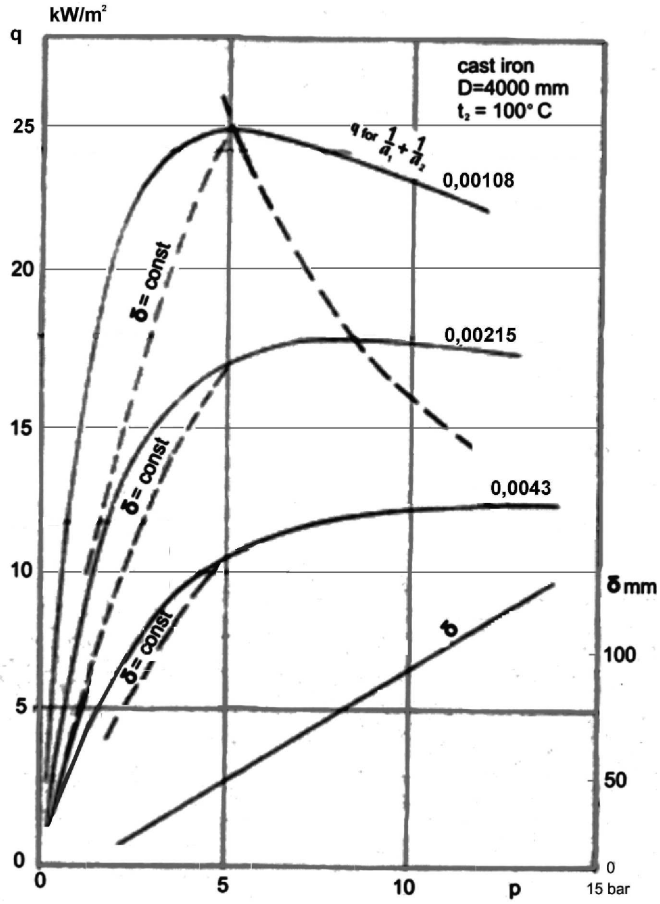

Fig. 4. Effect of the resistance to heat transfer on both sides of the cylinder wall on density of the heating stream for cast iron cylinders: p – steam pressure, α_1 – coefficient for "steam-to-cylinder wall" heat transfer, α_2 – coefficient for "cylinder wall-to-paper" heat transfer, q – heat flux

transfer on both sides of the cylinder wall (i.e. steam to cylinder and cylinder to paper heat transfers), the impact of the resistance to heat transfer through the wall itself, $\frac{\delta}{\lambda}$, is obviously more significant.

Moving forward in the above analysis, one can examine the change in heat flux stream per 1 kg of a cylinder mass. The corresponding relation, shown below, would also indicate a maximum, but at a lower steam pressures:

$$\frac{q}{\delta} = f\,(p) \tag{13}$$

Since manufacturing cost of the cylinder is not directly proportional to its weight, the actual maximum would be somewhere between the pressure corresponding to the maximum derived from relations 10 to 12 and the pressure derived from relation 13.

Conclusions

As it was mentioned at the beginning, the main purpose of this study was to explain the phenomena of heat transfer during paper drying process and to show why increasing pressure of the heating steam may not necessarily been the most economically wise way to improve the overall effectiveness of the drying section. Based on graphs presented in this study, one can argue that optimal and maximum pressure inside a cast iron cylinder should not exceed 7 bar for cylinders located in the center of the drying section, 5 bar for cylinders located just after the press section. The corresponding values for steel cylinders are 15 bar and 11 bar, respectively.

To achieve the optimal heat flux, as described in the above study, during the real-life process it is necessary to maintain an optimal steam pressure inside the cylinder.

One of the more interesting conclusions from this study is the finding that an optimal steam pressure for systems with a forced airflow around drying cylinders (i.e. closed cylinder hoods) is lower than for an older drying section designs that depended on a contact drying only. Therefore, the systems with effective, highly-productive closed cylinder hoods allows for application of cylinders with thinner walls.

In each case, the important thing is that selection of the optimal steam pressure and the corresponding cylinder wall thickness is based on the actual working conditions to which a given cylinder is or will be exposed to during its working life. Especially important is to evaluate conditions inside and nearby outside the cylinder, i.e. the tension at which paper is pressed against the cylinder surface and other design and process parameters discussed in more details in the above study. The graphs and relations derived in this study can be used as guiding tools to determine optimum steam pressure and the corresponding minimum required thickness of the cylinder walls.

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Optymalizacja ciśnienia pary grzejnej na wydajność cieplną cylindrów suszących

S t r e s z c z e n i e

W artykule przeprowadzono analizę warunków przepływu ciepła przez ścianki cylindra połyskowego, potraktowanego, jako naczynie cienkościenne.
Przeanalizowano wpływ wybranych parametrów konstrukcyjno-eksploatacyjnych (m.in. średnicy cylindra i ciśnienia pary) na gęstość strumienia ciepła w przypadku, gdy cylinder jest wykonany z żeliwa i ze stali.
Ustalono optymalne zakresy wartości ciśnień pary dla tych cylindrów, usytuowanych w różnych miejscach suszarni w maszynach papierniczych.