Intensification of Paper Drying on Drying Cylinders

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Abstract. One of the most energy-intensive processes is the drying process. Therefore, an important task is to reduce heat consumption for drying. Various ways to improve the drying devices of paper and cardboard machines are identified. The main disadvantages of these improvements are given. The limiting factor of heat transfer from water vapor to paper is established. The dependence of thermal resistance on the thickness of the condensate layer is given. The authors have developed a new design for condensate drainage. The developed design allows installing movable siphons without replacement of steam inlet heads of the old type (for fixed siphons) with their insignificant modernization and cutting of an annular groove inside the drying cylinder. This will ensure a minimum level of condensate and eliminate the possibility of suction of steam into the condensate return system. Additionally, this will reduce thermal resistance, heat loss, and reduce energy consumption for paper drying as a whole.

Introduction

Paper and cardboard production require large heat consumptions. The drying process is one of the most energy-consuming processes. Paper drying takes place on the drying cylinders of a paper-making machine. Depending on the mass of paper and the speed of the paper machine, the number of drying cylinders varies and can reach more than 200 units. The mass of a drying part is about 60 % of the total weight of the machine, and the cost of almost 50 % [1].

Water vapor is used to heat the drying cylinders, and a lot of energy resources are required to produce it. The heat recovery system allows reducing heat consumption partially.

Conductive Drying of paper on drying cylinders is combined with other heat sources. For example, infrared radiation is very common to intensify the drying process of paper and cardboard [2].

At present, one of the most effective ways to reduce the demand for heating on paper drying is to maximize the moisture content of the paper at the beginning of its drying. To do this, you need to intensify the previous process of paper pressing, which is the mechanical removal of moisture [3]. It is known that the cost of the thermal method of removing moisture from the material (drying) is 10–12 times higher than pressing. Thus, increasing the moisture content of the paper web by 1 % at the beginning of the drying process leads to an increased consumption of heat and steam by 5 %.

Reduction of energy consumption for drying paper will lead not only to the reduction of steam consumption but also to a decreased number of drying cylinders and metal-capacity of a paper machine as a whole.

Therefore, the critical task is to reduce the consumption of heat on the drying process. Besides, to reduce the cost of modernization, the improvement of existing structures is desired. This is usually cheaper than installing new constructions.

Literature Review

In practice, as a rule, the design of a drying cylinder is being improved. In general, a few directions of its modernization can be distinguished.

Firstly, the designers try to improve the contact of the paper web and the external surface of a drying cylinder. For this purpose, the authors suggest to cover the surface of the drying cylinder with chromium and to polish [4, 5]. This will reduce the air layer between the paper web and the drying cylinder's surface and improve the heat exchange between them.

Also, there are a number of literary sources that recommend maximizing the efforts to press a grid to a paper web. This will also improve the adhesion of the paper to the surface of a drying cylinder.

Many improvements are also aimed at improving the removal of condensate from the inner cavity of a drying cylinder. So the authors [6] offered the design of a drying cylinder inside of which condensation heat recovery unit is installed. It will suck a condensate in a whole series of nozzles. However, such a structure is difficult to fix inside and carry out further balancing.

There are similar technical solutions to improve the condensate removal process from the drying cylinders [7]. However, all of them complicate the process of making designs, their balancing and increase the content of metal of the device.

Such a decision is proposed by the authors [8, 9]. Steam supply and condensate return are happening directly near the inner surface of the drying cylinder. However, this complicates the construction of the cylinder and carrying out dynamic balancing. Besides, this nozzle layout can increase steam losses due to its suction by nozzles of a condensate return system.

Other authors [10] suggest installing additional turbulators of a condensation layer in the inside of the drying cylinder. This makes it possible to improve the heat transfer from steam to the inner surface of the cylinder through a layer of condensate. However, this cumbersome design causes problems similar to those the previous design have.

The authors [9] also suggest to create the turbulence of a condensate layer due to the flued inner surface of the drying cylinder. However, this solution causes additional difficulties for condensate transfer to the condensate return system and removing it outwards.

Also, to increase the intensity of the heat flow to the paper web authors [11] proposed the atypical construction of the drying cylinder shell. It is made by welding of steel square pipe sections to be joined. Inside them, hot steam is passed under high pressure. High strength pipes will maximize the vapor pressure and, consequently, its temperature. However, this design is difficult to be manufactured. Also, there are difficulties in removing condensate from the shell.

To reduce the heat resistance during heat conduction through the shell, the authors developed a construction [12], where the outer shell is made thinner compared to the typical designs. This design solution also complicates the production of the drying cylinder and the removal of condensate from the formed chambers in the shell of the drying cylinder.

To reduce heat loss through the side plates of the drying cylinder, authors [13] proposed to lessen their thermal conductivity by installing thermal insulation. This direction of improvement is prevailing and has various ways for its implementation.

So, there are many ways how to improve the designs of drying cylinders. However, most of these structures are fundamentally different from the typical drying cylinders used on papermaking machines. Therefore, this modernization requires the replacement of existing drying cylinders for new ones. This significantly increases the necessary costs and requires economic justification for such modernization.

The essential problem is to define the latest trends in modernization and the possibility of its implementation into the existing design of drying cylinders.

Research Methodology

3.1 Setting of limiting factor of heat transfer from water vapor to paper

As mentioned earlier, the process of drying the paper web by supplying water vapor inside the drying cylinder. Inside it, the steam condenses, forming a layer of condensate [14, 15].

Mathematical models of paper drying determine the amount of heat from steam to paper [16–18].

The amount of heat transmitted to the paper from condensation water vapor is calculated by the main equation of heat transfer:

$$Q = kf(t_s - t_p), \qquad (1)$$

where t_s, t_p – Temperature condensation vapor and paper temperature, in contact with the surface F of the cylinder. Kinetic coefficient K characterizes the speed (intensity) of transfer of heat from steam that condenses to the wet paper [19]. Its value is inversely proportional to the thermal strokes on the path of the thermal flux Q and is calculated from the following equation:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_{cyl}}{\lambda_{cyl}} + \frac{1}{\alpha_2}}, \qquad (2)$$

where $\frac{1}{\alpha_1}$ – the thermal resistance of heat transfer from condensing steam to the inner surface of the drying cylinder, $\frac{m^2 \cdot K}{W}$; $\frac{\delta_{cyl}}{\lambda_{cyl}}$ – the thermal resistance of the heat flux transferred due to thermal conductivity through the metal shell of the drying cylinder, $\frac{m^2 \cdot K}{W}$; $\frac{1}{\alpha_2}$ – thermal resistance in the cylinder-paper contact, $\frac{m^2 \cdot K}{W}$.

The heat transfer coefficient α_1 shows the rate of heat transfer from the steam to the inner surface of the drying cylinder. For low-speed machines, it means in the absence of a water ring; its value is about 4060–4640 $\frac{W}{m^2 \cdot K}$ [1]. For high-speed paper machines, where a water ring is present, its values are taken 2900–3500 $\frac{W}{m^2 \cdot K}$.

The drying cylinder is usually made of cast iron with a wall thickness $\delta_{cyl} = 0.025$-0.040 m. The thermal conductivity of cast iron λ_{cyl} is about 50 $\frac{W}{m \cdot K}$ [1].

The heat transfer coefficient α_2 shows the rate of heat transfer from the outer surface of the drying cylinder to the paper web [20], considering the imperfect contact between them. Its value varies in a range of 300–850 $\frac{W}{m^2 \cdot K}$ depending on the quality of contact between the surfaces

of the cylinder and the paper and the moisture content of the latter [1].

The following Table 1 gives a summary of all thermal resistances.

Table 1 – Thermal resistances, $10^{-4} \frac{m^2 \cdot K}{W}$

Thermal resistance	Minimum value	Maximum value
$\frac{1}{\alpha_1}$ (for low-speed paper machines)	2.155	2.463
$\frac{1}{\alpha_1}$ (for high-speed paper machines)	2.857	3.448
$\frac{\delta_{cyl}}{\lambda_{cyl}}$	5.000	8.000
$\frac{1}{\alpha_2}$	11.760	33.330

If there is sludge inside the drying cylinder, it must also be considered as additional thermal resistance. Therefore, it is essential to clean the inner surface of the cylinder periodically.

In existing paper machines, the speed of the paper web is more than 400 m/min; these are high-speed machines. Under such conditions, inside the drying cylinder, the condensate layer takes the form of a water ring, which moves with a small slip relative to the inner surface of the cylinder.

Therefore, for a more accurate calculation, it is desirable to consider condensate layer as an additional thermal resistance $\frac{\delta_{cond}}{\lambda_{cond}}$.

To remove condensate in high-speed machines, a rotating siphon is used together with a drying cylinder. However, many existing paper machines still operate with fixed siphons, which, as the speed of the machines increases, worse the removal of condensate from the drying cylinders and the drying of the paper as a whole.

The thickness of the condensate layer in the drying cylinder is not less than the value of the gap between the siphon head and the inner surface of the drying cylinder. For high-speed machines with movable siphons, this value is 1,5-2 mm. For low-speed machines, the gap is 4–5 mm.

A reasonably widespread practice is to upgrade existing low-speed machines [21]. It is possible to increase the speed of the paper machine and the formation of a water ring inside the drying cylinders. However, in the case of the old condensate return system with fixed siphons, the thickness of the condensate layer will be from 4–5 mm. This will significantly increase the thermal resistance and increase the consumption of heating steam.

Also, when the siphon head is located above the surface of the condensate layer, it is possible to absorb water vapor into the condensate return system. This will also increase steam consumption.

The installation of new drying cylinders requires significant investment. Replacing the steam condensate system with a new one is also costly enough. Overall, the replacement of fixed siphons on the mobile also requires the replacement of the steam inlet head on each drying cylinder.

Let us create the dependence of the thermal resistance $\frac{\delta_{cond}}{\lambda_{cond}}$ on the thickness of the condensate layer (Fig. 1).
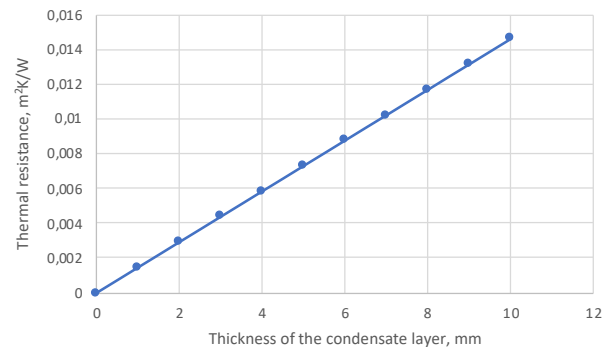

Figure 1 – Dependence of thermal resistance $\frac{\delta_{cond}}{\lambda_{cond}}$ on the thickness of the condensate layer

As shown in Figure 1, the thermal resistance of the condensate layer when fixed siphons are installed (respectively, a gap of 4–5 mm):

$$\frac{\delta_{cond}}{\lambda_{cond}} = (5.865–7.331) \cdot 10^{-3} \frac{m^2 \cdot K}{W}.$$

Comparing the obtained values of thermal resistance from the condensate layer with others (Table 1), it is seen that under these conditions, it is the largest.

Accordingly, it follows that the need to improve the condensate drainage system by increasing the speed of low-speed vehicles above 400 m/min.

3.2   Identification of design solutions to improve existing condensate drainage systems

Obviously, to reduce the thermal resistance of the condensate layer, it is necessary to reduce the thickness of this layer.

It is also desirable to reduce or completely eliminate the possibility of steam absorption into the condensate return system.

To achieve the latter, it is necessary that the siphon head of the condensate drainage system is immersed in a condensate layer. However, ensuring this position is possible with a sufficient level of condensate, which, in turn, will increase the thermal resistance.

To solve this problem, it is necessary to create an additional recess in the place where the siphon head is close to the inner surface of the drying cylinder. This will ensure the deepening of the siphon into the condensate layer, but will provide a minimum layer of condensate across the width of the drying cylinder (Fig. 2).
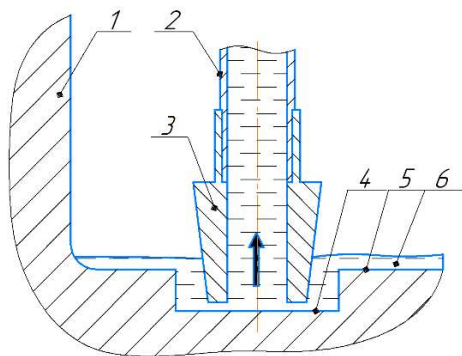
Figure 2 – Placement of the siphon head in the drying
cylinder after modernization: 1 – drying cylinder;
2 – siphon; 3 – siphon head; 4 – annular groove;
5 – the inner surface of the drying cylinder;
6 – the layer of condensate

To accurately position the siphon head and maintain the required clearance between it and the inner surface of the drying cylinder, the siphon head must contain a mechanism for precise movement.

For better fixation of the siphon in the drying cylinder, it can be additionally attached to the cover of the drying cylinder. For these purposes, cover lugs can be used to attach the cover to the machine during its processing.

To be able to use the old-type steam head (for fixed siphons) it is necessary to remove the outer pipe for condensate return. The tightness of the condensate return system will be ensured by the presence of a pin of the drying cylinder, a graphite seal, and a bellows. Besides, in the bellows there will be condensate instead of steam, which reduces the negative impact in the case of its rupture.

Results

Considering the technical solutions described in chapter 3.1, we have proposed an upgrade of the drying cylinder. It consists in replacing of a fixed siphon with a movable siphon; additionally attaching movable siphons to the side cover of the drying cylinder, creating an annular groove on the inner surface of the drying cylinder, in which the siphon heads are placed below the level of the inner surface of the cylinder; the old steam head of the fixed siphon has been changed to enable it to use together with movable siphons.

Discussion

This development is designed to upgrade existing drying parts of paper machines to increase their speed and, accordingly, productivity with minimal capital investments based on the installed equipment.

In work [1], there is another variant of how the movable siphon is fixed inside the paper machine. However, the way of fixing the movable siphon with a spacer bar increases metal consumption. Besides, in this case, there is only one or a maximum of two movable siphons. In the proposed design, four siphons are used, which has a positive effect on the quality of condensate return.

Conclusions

Currently, there is a developed design of drying cylinders with movable siphons. However, in the case of modernization of drying cylinders of low-speed paper machines, such a design also requires replacement and steam inlet heads. Due to a large number of drying cylinders in paper machines, this demands a substantial investment.

The developed design allows installing movable siphons without replacement of steam inlet heads of the old type (for fixed siphons) with their insignificant modernization and cutting of an annular groove inside the drying cylinder.

This will ensure a minimum level of condensate and eliminate the possibility of suction of steam into the condensate return system. This will reduce thermal resistance, heat loss, and energy consumptions for paper drying as a whole.

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