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MODELLING OF THE TECHNOLOGICAL PROCESS OF REMOVING CARDBOARD SCRAPS IN THE DIE-CUTTING SECTION

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Pneumatic systems are widely used in printing production. Pneumatics are used to transport, capture and hold sheet material during the finishing process. The conducted research is aimed at identifying factors affecting the efficiency of the pneumatic system, which includes a rotating perforation cylinder. In particular, such factors include air temperature and humidity, which may later affect the construction features of the pneumatic system.

In the research process, a series of simulations is conducted using the SolidWorks system. The data obtained from the simulations form the basis of a theoretical study on the characteristics of rarefied air in the process of removing cardboard scraps. The scientific paper proposes an algorithm for calculating the power of the pneumatic system of the perforating cylinder and the distribution of rarefied air flows within the working area of removing cardboard scraps.

The obtained results of analytical studies are presented in the form of graphs characterizing the general parameters of the pneumatic system of the perforation cylinder, which will be taken into account during the further experimental design of the equipment for removing cardboard scraps.

Keywords: *die-cutting, cardboard sweep, perforation cylinder, rarefied air, carriage, transport system.*

Introduction. Pneumatic systems are widely used in printing. One of the directions of their application is the transportation and fixation of sheet materials during technological processing, in particular, in the manufacture of cardboard packages.

The problem of irregular distribution of rarefied air in single-chamber pneumatic cylinders negatively affects the operational characteristics of the machine. Namely, there is low-quality capture of the sheet and its positioning.

Methods. Development of new and improvement of existing equipment for the production of packaging is an actual and perspective direction [1-8].

During the modelling of the operation of the rotating perforation cylinder in the *SolidWorks* system, a number of structural flaws were discovered, which were accompanied by inaccurate positioning of the sheet material.

Based on the analysis of the existing equipment containing pneumatic cylinders, it was established that in most cases the only means of correcting the uneven distribution of rarefied air inside the drum is a general increase in the power of the pneumatic system. This approach is simple to implement, but not effective from the point of view of energy consumption and, as a result, the cost of manufactured products.

Results. The purpose of the research is to identify the irregular distribution of rarefied air flows within the pneumatic cylinder and to develop a mathematical apparatus for conducting theoretical calculations.

Conducting an analysis of the operation of a single-chamber and two-chamber pneumatic cylinder according to the proposed methodology. Presentation of research results and their comparison with computer simulation results.

Discussion. The usage of pneumatic systems in die-cutting equipment have a decisive place due to significant advantages in efficiency and functionality compared to classic structural solutions. Despite significant technological advantages, the issue of energy efficiency of the section is still important.

In the course of the research, mathematical calculations were carried out for sections of different designs in order to analyse the energy efficiency characteristics. Therefore, in order to obtain an array of representative results that would be convenient for comparison and perception, calculations were carried out for a specified cardboard format of 297 ×420 mm, which corresponds to the A3 format common in printing. However, the proposed method of calculation and the obtained results can be applied without making changes to other variants of processed materials. Physical and mechanical characteristics of cardboard are shown in Table 1.

Table 1

Physical and mechanical characteristics of cardboard

Characteristics of KC cardboard	
Mass of 1 m2, g	1650±125
Thickness, mm	2,2
Absolute compressive strength, MPa	1,96
Lateral compressive strength, kN/m2	4,9
Resistance to transverse delamination, H	64
Absorption at one-sided wetting, g	30

For further comparative calculations, we use the design of a rotating cylinder with an internal perforated chamber. The initial parameters of the calculation of the system with a double cylindrical chamber are shown in Table 2.

Table 2

Initial calculated values of the system with a double cylinder

№	Length of the cylinder, L, mm	Diameter of the cylinder, D, mm	Area of the cylindrical hole, mm2	Number of holes on the surface of the cylinder, n	Area of the contact zone, S, mm2	Air density in the working area, ρ, kg/m3	Adiabatic coefficien, γ	Tempera-ture, t, °C
1	450	100	4.9	5456	124740	1.204	1.4	15
2					62370			
3					31185			
4					124740	1.168		35
5					62370			
6					31185			
7					124740	1.060		60
8					62370			
9					31185			

To calculate the necessary pressure difference created by the pneumatic system to hold a sheet of cardboard during processing, we use the following formula:

$$P = \frac{m \cdot \left(g + \frac{1}{\mu} \right) + m \cdot \omega^2 \cdot r}{S} \tag{1}$$

where *m* is the mass of the sheet, *g* is the gravitational constant, μ is the coefficient of friction between the surfaces, ω is the angular velocity, *r* is the radius of the cylinder, *S* is the area of the holes. The given formula takes into account the main factors affecting the fixation and movement of the sheet.

Having the necessary value of the pressure drop for fixation, you can find the air flow during operation:

$$Q = \sqrt{\frac{2 \cdot \gamma}{\gamma - 1} \cdot \frac{p_o}{\rho} \cdot \left(1 - \left(\frac{p}{p_o} \right)^{\frac{\gamma - 1}{\gamma}} \right)} \cdot S \tag{2}$$

where γ is the adiabatic coefficient, p_o is the pressure outside the section, ρ is the air density.

The obtained value of air flow can give a general idea about the necessary power for the operation of the rotary die-cutting section of the pneumatic system. However, for a more accurate calculation, additional internal and external parameters should be taken into account.

One of the important parameters affecting the efficiency of the pneumatic system is volume resistance. Volumetric resistance characterizes pressure losses on the path of rarefied air transportation caused by the geometric features of the pneumatic system. To calculate the volume resistance of the system, we use the formula:

$$\Delta P=\frac{\frac{\lambda\cdot L}{D}\cdot\rho\cdot\left(\frac{Q}{S}\right)^{2}}{2} \tag{3}$$

where L is the length of the pneumatic cylinder, D is the diameter of the pneumatic cylinder, and λ is the Darcy coefficient.

However, the mutual dependence of the volume flow of air and the volume resistance of the pneumatic system leads us to the need to carry out a number of additional calculations. The following formula illustrates the air flow calculation for a given stage:

$$Q_i=\sqrt{\frac{2\cdot\gamma}{\gamma-1}\cdot\frac{p_o}{\rho}\cdot\left(1-\left(\frac{p+\frac{\frac{\lambda\cdot L}{D}\cdot\rho\cdot\left(\frac{q_{i-1}}{S}\right)^{2}}{2}}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\right)}\cdot S \tag{4}$$

Since the displacement of the volume flow values becomes smaller with each step, the value $i = 5$ is optimal for calculation with sufficient accuracy.

An important factor that significantly affects the operation of the pneumatic die-cutting section is humidity. A change in air humidity has a significant effect on its density and how it changes with temperature.

Due to the high complexity of calculating the properties of moist air, approximate formulas are used to calculate its individual characteristics. By using additional coefficients, they are able to provide the appropriate level of accuracy while significantly reducing the necessary calculations. The error of such calculations can range from 0.01% to 0.2%, which is allowable for a specific case.

So, use the following formula to calculate the density of moist air:

$$\rho=\frac{\frac{\left(e^{20.386}-\frac{5132}{T+273}\right)\cdot R_h}{T}}{461.495}+\frac{\frac{P-\left(e^{20.386}-\frac{5132}{T+273}\right)\cdot R_h}{T}}{287.058} \tag{5}$$

where R_h is the Reynolds number.

However, for the correct operation of the pneumatic section, it is necessary to take into account not only the peak pressure values in individual contact zones with the workpiece, but also the uniformity and sufficiency of the air flow in the working zone of contact between the cylinder and the cardboard sheet.

Preliminary computer simulations in the *SolidWorks* system show that in a single-chamber pneumatic cylinder, the air flow significantly weakens with distance from the inlet of the vacuum pump nozzle. This can have a significant negative impact on the reliability of fixing cardboard sweeps of a complex configuration. Therefore, the characteristics of the air flow are an integral part of the calculation of the pneumatic cylinder.

There are several possible approaches to the calculation of air flow, but each of them has a disadvantage in the form of repeatability, which significantly limits the application of each of them. The most common of them is the Navier-Stokes equation. However, the biggest problem in its application is its large computational capacity, which makes it suitable for use only with computer software.

The need to create a mathematical apparatus for calculating the characteristics of a pneumatic cylinder with less accuracy, but faster and without the use of a PC, leads to the need to use simpler equations. How is the formula for calculating the flow of matter through an opening:

$$Q_o = C \cdot S_o \cdot \sqrt{2 \cdot \rho \cdot P} \tag{6}$$

where *C* is the flow rate through the opening, S_o is the area of the opening, ρ is the air density, *P* is the pressure difference.

So, Figure 1 shows a simplified design of a perforated pneumatic cylinder with holes located in its base. The schematically shown holes will later be used to hold the cardboard scraps with thin air.

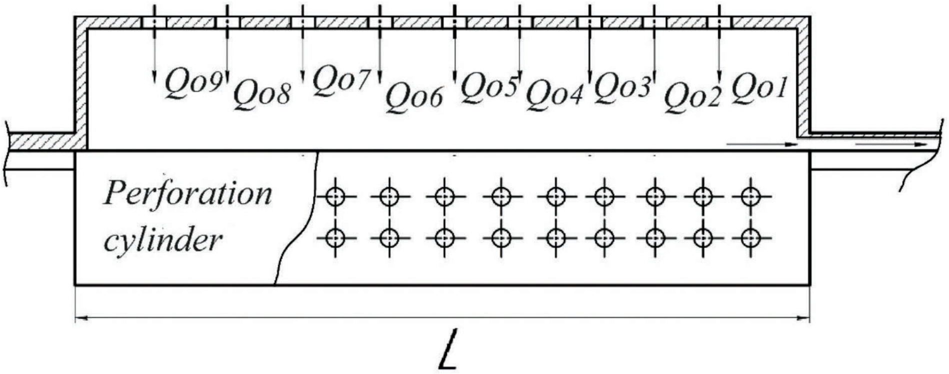

Fig. 1. Simplified design of the perforation pneumatic cylinder

The main problem of simplifying the calculation is the need to determine the coefficient C, which can vary significantly depending on the design of the pneumatic system and often requires analytical selection from an already available array of data or literary sources.

In our case, such a source of data can serve as a preliminary result of a simulation carried out using the SolidWorks system, which is presented as a expression in Figure 2.

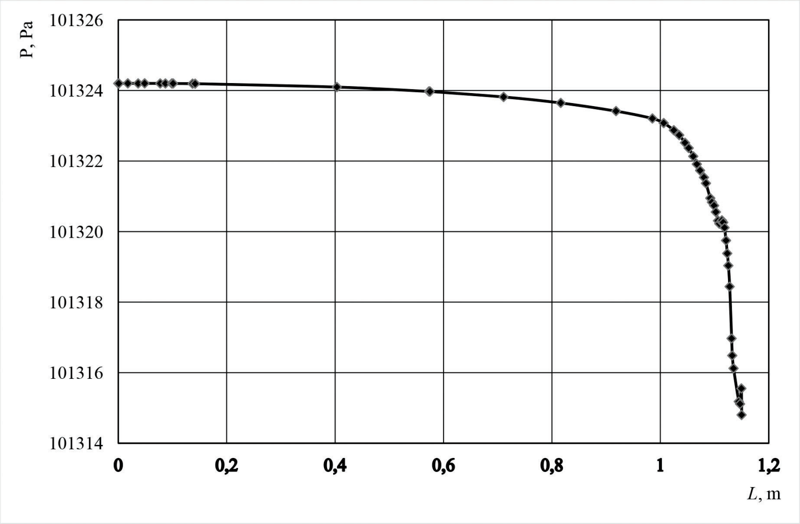

Fig. 2. Pressure dependence along the contact line *L* in a single perforation pneumatic cylinder

The graph illustrates the change in the flow of rarefied air with a minimum load in the pneumatic system depending on the distance to the nozzle of the vacuum pump according to the following expression:

$$Q_{o9} < Q_{o8} < \dots < Q_{o2} < Q_{o1}. \quad (7)$$

It is important to note that the graph of pressure changes along the contact zone changes. Equating the coefficient characterizing the air flow through the given hole through $C = e^{-L}$ we get the following formula: $Q_o = e^{-L} \cdot S \cdot \sqrt{2 \cdot \rho \cdot P}$. Where L_i is the current distance from the hole to the vacuum pump nozzle.

Figure 3 shows the results of mathematical calculations consumption the flow rate of rarefied air passing through the hole d_o = 2.5 mm. The dependence is characterized by the distance to the vacuum pump nozzle depending on the temperature conditions t1=15°C, t2=35°, t3=60°.

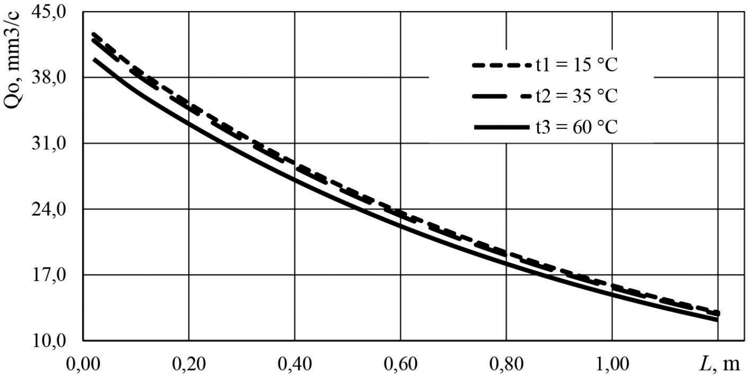

Fig. 3. Dependence of rarefied air consumption for d_o = 2.5 mm on the distance to the vacuum pump nozzle for temperature regimes t1=15°C, t2=35°, t3=60°

As can be seen from Fig. 3, the air flow passing through the hole is inversely proportional to its distance from the nozzle of the vacuum pump. That is, there is an 88% decrease in flow. Comparing the calculated data with the simulation data in Fig. 2, it can be seen that the calculated model offers a less sharp drop in flow.

The dependence of the volumetric air flow rate on the temperature for a given area of clipping capture S1 = 0.31 m2, S2 = 0.62 m2 and S3 = 1.24 m2 is shown in Figure 4. As can be seen from the graph, regardless of the overlap area of the sheet, when at low humidity values, the volumetric air flow varies within 7% with temperature changes.

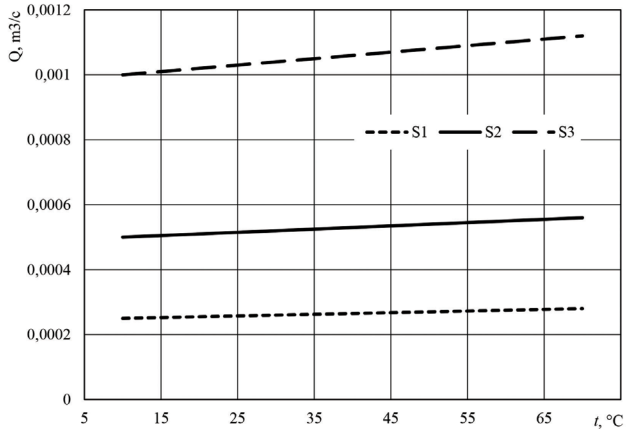

Fig. 4. Dependence of volumetric air flow on temperature for a given area of clippings S1, S2, S3

The dependence of the increase in air consumption dQ on the temperature t at humidity 10%, 45% and 80% is shown in Figure 5. As we can see, air humidity significantly affects its density and, as a result, its volume flow during operation. At the maximum calculated temperature values, the change in volumetric air flow with a subsequent increase of one degree at 80% humidity is 2.8 times greater than the similar value at 10% humidity.

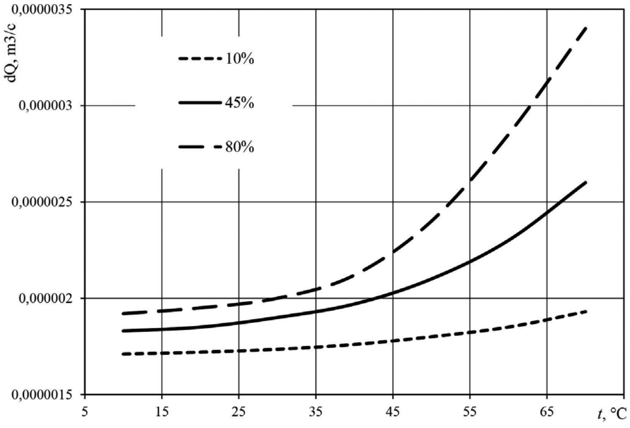

Fig. 5. Dependence of the increase in air consumption *d*Q on temperature *t* at humidity of 10%, 45% and 80%

As a result, this parameter makes the system more sensitive to ambient temperature fluctuations and must be taken into account when designing machines, even with classical balancing of the clamping force due to an increase in total power, since significant losses of force at the remote end of the cylinder can lead to errors in the operation of the machine.

Conclusions. As it can be seen from the presented graphic dependencies, the required power of the pneumatic system is highly dependent on the environmental conditions in which the work takes place. Temperature and humidity affect not only the characteristics of the processed materials, but also the overall performance of the pneumatic system. This, in turn, has a significant impact on the performance of work by die-cutting pneumatic sections and can lead to abnormal situations when the calculated conditions are exceeded.

At the same time, the design of the rotary drum also has a significant impact on the efficiency of the distribution of air flows in the pneumatic system, and making changes to its design can significantly reduce the required power reserve of the system for leveling operational deviations. This will significantly increase the efficiency of the pneumatic system and will positively affect the economic feasibility of using automatic die-cutting machines for small circulations of products.

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МОДЕЛЮВАННЯ ТЕХНОЛОГІЧНОГО ПРОЦЕСУ ВИДАЛЕННЯ КАРТОННИХ ОБРІЗКІВ У ВИСІКАЛЬНІЙ СЕКЦІЇ

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Пневматичні системи знаходять широке застосування в поліграфічному виробництві. Пневматичні пристрої використовуються для транспортування, захоплення та утримування аркушевого матеріалу під час технологічного процесу обробки. Тому у багатьох випадках нерівномірне розподілення розрідженого повітря у однокамерних пневматичних циліндрах негативно впливає на експлуатаційні характеристики спеціалізованого штанцювального обладнання. А саме, спостерігається неякісне захоплення аркуша і його подальше позиціювання.

Моделювання технологічного процесу переміщення картонної розгортки та послідовне видалення її обрізків в обертовому перфораційному циліндрі виявило ряд конструктивних недоліків, що супроводжувались не точним позиціюванням матеріалу. За допомогою системи автоматизованого проєктування SolidWorks виявлено нерівномірності розподілу потоків розрідженого повітря в межах пневматичного циліндра. Використано математичний апарат для проведення теоретичних розрахунків щодо аналізу роботи однокамерного та двокамерного пневматичних циліндрів.

На основі аналізу пневматичних циліндрів встановлено, що у більшості випадків єдиним засобом корегування нерівномірності розподілу розрідженого повітря всередині барабана є загальне збільшення потужності пневматичної системи. Такий підхід є простим в реалізації, однак не ефективним з точки зору витрат енергії та як наслідок собівартості виготовленої продукції.

Проведене дослідження спрямоване на виявлення чинників, що впливають на ефективність роботи пневматичної системи у складі обертового перфораційного циліндра. Зокрема до таких чинників належать температура повітря та його вологість, які в подальшому можуть впливати на конструкцію пневматичної системи. Проведені серії симуляцій з використанням системи SolidWorks лягли в основу теоретичного дослідження щодо характеру і поведінки розрідженого повітря у процесі видалення обрізків картонних розгорток. В роботі запропоновано алгоритм розрахунку потужності пневматичної системи перфораційного циліндра та розподілення потоків розрідженого повітря в межах робочої зони видалення картонних обрізків. Отримані результати аналітичних досліджень представлені у вигляді графіків, що характеризують загальні параметри пневматичної системи перфораційного циліндра. Проведені дослідження будуть враховуватись при подальшому проєктуванні обладнання для виготовлення картонних розгорток.

Ключові слова: *висікання, картонна розгортка, перфораційний циліндр, розріджене повітря, каретка, транспортувальна система.*

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