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Cooling of Rubber Embossing Cylinder for Tissue Paper

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ABSTRACT

Traditional embossing processes applied to papers generate significant amounts of heat, leading to the degradation and decreased efficiency of the rubber cylinder, a critical component of the machine, over time. This study investigates a novel internal cooling system designed to address this issue and extend the lifespan of the rubber cylinder. Experiments were conducted using tap water and ethylene glycol aqueous solution as coolants at a machine speed of 350 m/min and a specified pattern density. The results suggests that the non-cooled cylinder started to deteriorate at a surface temperature of approximately 46 °C. However, with the implemented cooling system, the surface temperature was effectively maintained at 4-5 °C below this threshold, significantly extending the operational life of the rubber cylinder. Therefore, this study emphasizes the effectiveness of internal cooling in mitigating heat-induced damage and extending the lifespan of embossing cylinders.

Temizlik Kâğıdı Gofraj Sistemindeki Lastik Silindirin Soğutulması

ÖZ

Temizlik kağıtlarına uygulanan geleneksel gofraj işlemleri, makinenin önemli bir bileşeni olan kauçuk silindirin zamanla bozulmasına ve verimliliğinin düşmesine neden olan önemli miktarda ısı üretir. Bu çalışmada, bu sorunu çözmek ve kauçuk silindirin ömrünü uzatmak için tasarlanmış yeni bir dahili soğutma sistemi incelenmiştir. Deneyler, soğutucu olarak musluk suyu ve etilen glikol sulu çözeltisi kullanılarak 350 m/dakika makine hızı ve belirli bir desen yoğunluğu altında gerçekleştirildi. Sonuç olarak, soğutulmayan silindir yaklaşık olarak 46 °C yüzey sıcaklığında bozulmaya başladı. Bununla birlikte, uygulanan soğutma sistemiyle, yüzey sıcaklığı bu eşik değerin 4-5°C altında etkin bir şekilde korundu ve kauçuk silindirin çalışma ömrü önemli ölçüde uzatıldı. Bu nedenle, bu çalışmada dahili soğutmanın ısı kaynaklı hasarı azaltma ve kabartma silindirlerinin ömrünü uzatmada etkili olduğu gösterilmektedir.

Anahtar Kelimeler: Gofraj, soğutma, temizlik kağıdı, döner silindir

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1. Introduction

The embossed pattern on tissue paper is achieved using an embossing machine integrated into the tissue paper production lines, as shown in Figure 1. This process involves applying pressure between a steel embossing cylinder with a negative pattern and a rubber cylinder rotating in the opposite direction at the same speed [1]. Consequently, patterns are imprinted on the tissue paper flowing continuously between the two cylinders. However, the rubber cylinder undergoes wear and deformation over time as the system operates. The extent of rubber cylinder deformation is primarily driven by excessive surface temperature, which is influenced by various factors such as machine speed, pattern shape, pressing force, and pattern density.

The rubber cylinder used in the embossing process consists of natural rubber adhered to a steel cylinder with a negative embossing pattern. The surface temperature of the rubber cylinder increases because of the pressure applied by the negative pattern embossed steel cylinder [1]. The pressure must surpass a certain threshold to create patterns, although excessive pressure can accelerate the deformation of the rubber cylinder, thereby reducing its lifespan [2]. Additionally, the machine operating speed (cylinder revolution speed) and the pattern density of the steel embossing cylinder also affect the temperature increase on the rubber cylinder surface. Consequently, the temperature increases on the rubber cylinder surface limits the machine operating speed and pattern selection. To achieve high-quality production and optimal performance, it is imperative to regulate the temperature increase on the rubber cylinder surface. Otherwise, the rubber cylinder becomes unusable once it reaches a certain threshold temperature.

Embossed pattern quality depends on several critical parameters required for the embossing process. These parameters include roller speed, embossing temperature, and roller embossing pressure [3]. By controlling and optimizing these variables, it is possible to achieve the desired pattern outcomes with precision and consistency. It is important to control these factors to ensure the production of high-quality embossed patterns on tissue paper.

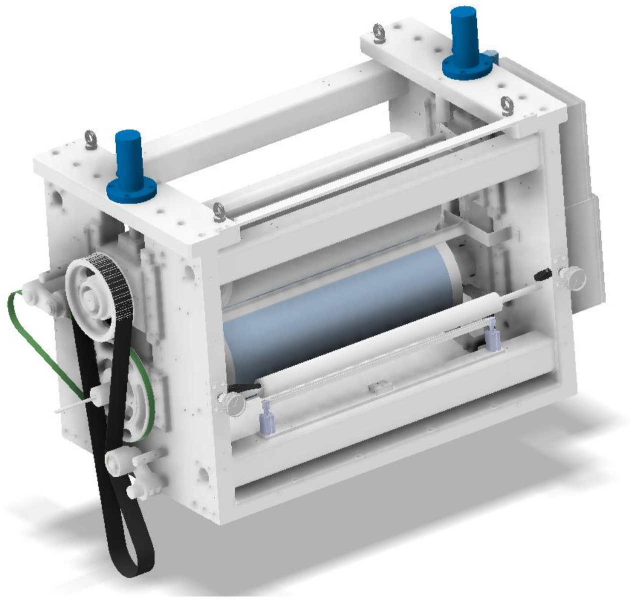

Figure 1. Embossing system

Researchers have been exploring ways to improve the life of the rubber cylinder, including using different materials, shapes, and adding cooling systems. Recent studies have shown the effectiveness of cooling systems for similar geometries. For instance, Fagan [4] and Fagan and Kim [5] designed a cooling system for a cylinder with a similar structure to maintain the desired temperature and prevent overheating. This system employed a nested and interlocked structure, evenly distributing air to 15 cooling slots along the embossed perimeter to facilitate the cooling process. Ma et al. [6] conducted numerical analyses on the use of a cooling cylinder for the continuous cooling of a thin rubber film flowing over a cylinder. Their study concluded that the temperature of the rubber film entering the cylinder significantly affected the cooling efficiency, whereas the width of the rubber film had minimal influence. Deng et al. [7] studied the polymer flow behaviour in roll-to-roll (R2R) hot embossing for continuous micro/nanostructure fabrication on polymers. Analysing micro-pyramids on PVC film with a 3D finite element model, they examined deformation and recovery during filling and remoulding. The temperature distribution showed notable gradients due to poor thermal conductivity, impacting creep strains. Effective cooling reduced pyramid recovery, especially at high mold temperatures.

Perez et al. [8] used gas as a cooling fluid in a comparable cooling system. They adopted a dual cryostat topology for the ASuMED motor, featuring separate cryostats for the rotor and stator. Their study recommended an externally controlled cooling system with forced gas circulation for optimal rotor cooling. The key factors considered were critical heat transfer and the influence of rotor stack temperature on cooling effectiveness.

Li et al. [9] studied micropyramid array fabrication on EVA copolymer films via roll-to-roll hot embossing. They found that EVA rheology correlates with micropyramid height. Films with 28% VA content, embossed at 60°C, exhibit high transmittance and are suitable for various applications. Optimal demoulding occurs at 40–60 °C, particularly with low VA content. The study introduced frequency-dependent viscosity for the demoulding analysis, showing the impact of viscosity and relaxation on micropyramid height. Li et al. [10] successfully produced micropyramid arrays on transparent PETG films by optimizing the applied force, roller temperature and speed for array quality. This study demonstrated the practical feasibility of fabricating micropyramid arrays on PETG films via roll-to-roll hot embossing, providing valuable insights for industrial applications.

Vieira et al. [11] investigated the impact of engraving finishing geometry on tissue paper properties during embossing. They observed that while straight finishing geometry led to higher individual hand-feel values, round finishing geometry enhanced softness in two-ply prototypes. Hand-feel values decreased with increased bulk, especially for micropatterns, but liquid droplet spreading kinetics were unaffected by finishing geometry. Finite element modelling revealed that round patterns left more pronounced marks on tissue paper, which was correlated with increased bulk. This modelling tool aids in optimizing process parameters and minimizing trial and error. This study highlights the significance of finishing geometry in embossing and provides valuable insights into tissue paper product properties.

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Morega [12] developed a small-power HTS synchronous motor prototype and explored cooling technologies for HTS field winding. They proposed supercooled nitrogen as an efficient and economical option but recommended cooling the HTS coils with liquid Ne for optimal performance. This study involved numerical simulations and mathematical modelling of heat transport in the stator, using 2D and 3D simulations to assess heat transfer properties and thermal loads. Various heat transfer mechanisms were found to influence the thermal stability of the motor, as determined by these simulations.

The influence of pattern type and density as well as the sensitivity of embossed pattern depth to preheating and cooling were investigated by Kim et al. [13]. They identified key factors affecting embossed pattern quality in roll-to-roll hot embossing and investigated time-dependent heat transfer effects using custom preheating and cooling systems. The results revealed that extended preheating time significantly influences embossed depth, whereas substrate cooling effects vary. In addition, they found that horizontal patterns with lower density yield larger embossed depths. This review sheds light on the importance of considering duration factors in heat transfer for roll-to-roll hot embossing, particularly concerning mold pattern characteristics.

Considering the high flammability of the cooling fluid and the abundance of tissue paper dust, implementing a gas-based cooling system poses significant safety hazards in this environment. Due to the risk of fire, a liquid-based approach was adopted instead. Compared to gas-based systems, liquid cooling offers several advantages in this context [14]. Primarily, liquids pose a lower fire risk than flammable gasses. Additionally, liquid coolants provide better heat transfer efficiency, allowing for effective cooling of the rubber cylinder surface. By circulating the liquid, heat is efficiently dissipated, maintaining the rubber cylinder within the ideal temperature range. Finally, liquid-based cooling allows for flexibility in coolant selection and temperature control, ensuring optimal operating conditions for the embossing process.

This study focuses on the inability to apply external cooling for rubber embossing rollers, which is a significant challenge in paper tissue manufacturing. While advancements have been made in embossing technology, addressing the heat-induced degradation of rubber cylinders remains a crucial area with limited existing research. This study aims to fill this gap in the literature by investigating novel internal cooling techniques to significantly extend the operational lifespan of rubber cylinders. This study also focuses on controlling the surface temperature increase of these cylinders within embossing machines. The study will involve comprehensive research into rubber cylinder design and materials, the development of a novel internal cooling system, experimental testing with prototypes, meticulous data analysis, and a comprehensive evaluation of the outcomes.

2. Materials and Methods

2.1. Cooling of the Cylinder

Preventing the temperature increase on the surface of the rubber cylinder is a critical parameter for extending its lifespan and increasing machine operating speed. Due to its low thermal conductivity [15] and surface-based heating, external cooling would be the ideal solution. However, implementing an external cooling system to prevent temperature increases on the surface of the rubber cylinder during operation is impractical because of the prevailing working conditions. The presence of paper dust, particularly in the working environment, requires internal cooling through the cylinder.

Figure 2 shows the geometry of the rubber cylinder. Heat transfer calculations were conducted by considering only conduction in the heat transfer process while neglecting other heat transfer mechanisms. In this context, upon examining the cross-section of the design, a resemblance to a bundle of pipes is noted. Heat transfer calculations were executed based on conduction, similar to heat transfer calculations in a pipe bundle, to determine heat loads and resistances. The necessary heat load to achieve the desired surface temperature, along with the requisite cooling fluid temperature and flow rate, was determined.

As previously stated, because of the prevailing working conditions, external cooling of the rubber cylinder surface by direct contact is unfeasible. Therefore, internal cooling from within the cylinder is expected to indirectly cool the rubber cylinder surface. In this regard, the temperature at point T_3 must be maintained as low as possible relative to the maximum temperature that the rubber can withstand. The temperature value at point T_1 is computed based on the T_3 temperature.

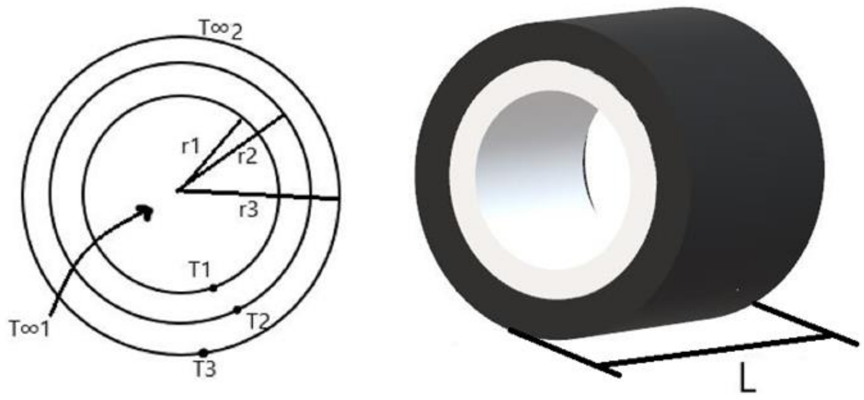

Figure 2. Rubber cylinder geometry

The total thermal resistance for multilayered cylindrical or spherical shells can be calculated as follows:

$$R_{\text{Total}} = R_{\text{Conv.i1}} + R_{\text{Cyl.1}} + R_{\text{Cyl.2}} + R_{\text{Conv.i2}} \quad (1)$$

$$= \frac{1}{h_{Conv.i1}A_1} + \frac{ln(\frac{r_2}{r_1})}{2\pi L k_{\text{cyl1}}} + \frac{ln(\frac{r_3}{r_2})}{2\pi L k_{\text{cyl2}}} + \frac{1}{h_{Conv.i2}A_2} \quad (2)$$

$$A_{1=2\pi r_1 \text{L}} \text{ ve } A_{2=2\pi r_3 \text{L}} \quad (3)$$

The heat transfer rate (Q) is given by

$$Q = \frac{T_{\infty 1} - T_{\infty 2}}{R_{\text{Total}}} \quad (4)$$

The heat energy of the cooling fluid, which is used as the heat energy medium, can be calculated as follows:

$$Q = mc_p\Delta t \quad (5)$$

The values r_1, r_2, and r_3 used in the formulas represent, respectively, the inner diameter of the steel cylinder, the outer radius of the steel cylinder or the inner radius of the rubber coating, and the outer radius of the rubber coating (see Figure 3). R_{Total}, $R_{Conv.i1}$, $R_{Cyl.1}$, $R_{Cyl.2}$, and $R_{Conv.i2}$ represent, respectively, the total heat, convective heat transfer for the coolant, heat conduction through the steel cylinder, heat conduction through the rubber, and convective heat transfer for the air. A_1 and A_2 represent, respectively, the inner surface area of the steel cylinder and the outer surface area of the rubber coating. The mass flow rate, specific heat capacity of water, and temperature difference are represented by m, c_p and Δt, respectively. $T_{\infty 1}$ and $T_{\infty 2}$ represent the temperatures of the fluid or surroundings on the inner and outer sides of the system.

In the context of the presented formulas, Figure 3 illustrates the meanings of r_1, r_2, and r_3 as the inner diameter of the steel cylinder, outer radius of the steel cylinder or inner radius of the rubber coating, and outer radius of the rubber coating, respectively.

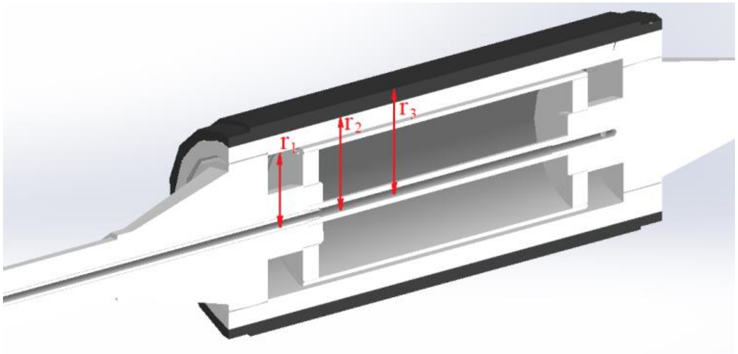

Figure 3. Cross-sectional view of the cylinder and its radii

2.2. Experimental Study

Figures 4a and 4b show the embossing machine group used in these experiments and the resulting pattern, respectively. The process of imprinting patterns onto tissue paper involves the steel embossing cylinder, featuring negative embossed patterns, rotating at a specified speed while exerting pressure against the rubber cylinder. The rubber cylinder rotates in the opposite direction at the same speed. This configuration transfers the patterns onto the tissue paper as it flows continuously between the two cylinders.

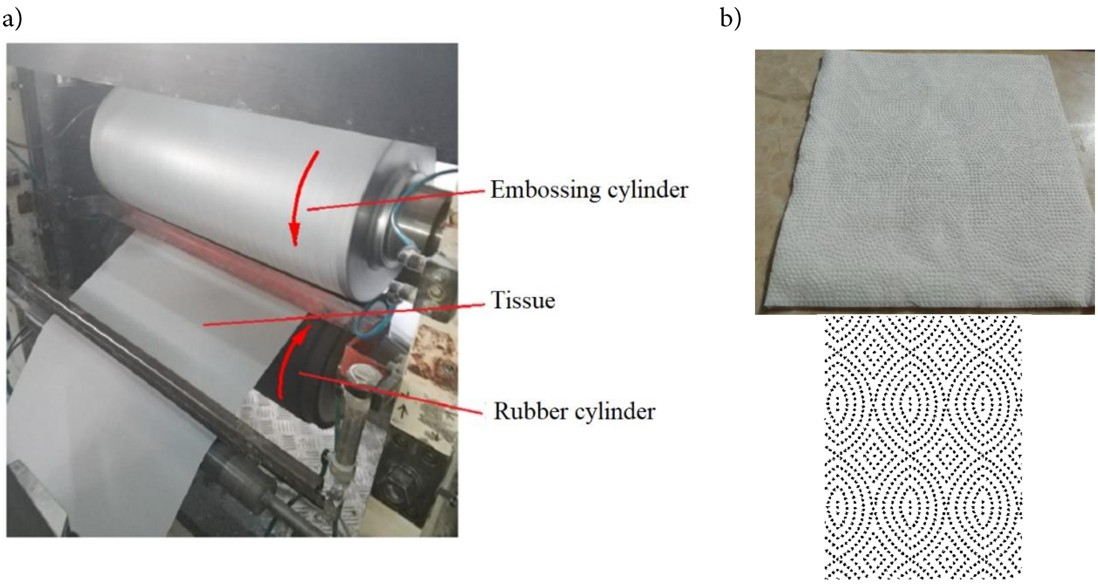

Figure 4. a) Embossing machine used in the experiment and b) created pattern

The embossing machine shown in Figure 4a operated at a speed of 350 m/min, causing the cylinders to rotate at approximately 440 rpm. During design studies, temperature fluctuations on the rubber cylinder's surface were measured within the operational environment using a laser thermometer and thermal camera. Based on these observations, an internal cooling system for the rubber cylinder was designed and prototyped. Subsequently, experiments were conducted with the fabricated prototype.

An SMC-HRSE-024 liquid circulation chiller was employed to circulate the liquid within the cylinder of the cooling system. A rotating head facilitated the liquid's inlet and outlet. Cold fluid entered the cylinder through the inlet pipe (1), illustrated in Figure 5. This inlet pipe (1) was connected to the cylinder shaft (2), with teeth left vacant to ensure liquid exit. Cold liquid was introduced into the system through the apertures depicted in Figure 5 (6). Upon entering the cylinder, the cold liquid traversed through the inner cylinder (5) and the steel cylinder (7), diminishing the volume of the cylinder's inner space. Heat transfer occurred between the steel cylinder (7) and the liquid during this phase. Subsequently, heat exchange between the steel and rubber cylinders cooled the latter.

The heated liquid exited the system through outlet apertures (3), flowing between the cylinder shaft (2) and inlet pipe (1) via the rotating head. This cooled fluid circulated continuously throughout operation. Table 1 presents data obtained from observations of the current model running with the cooling system, under the specified operating conditions.

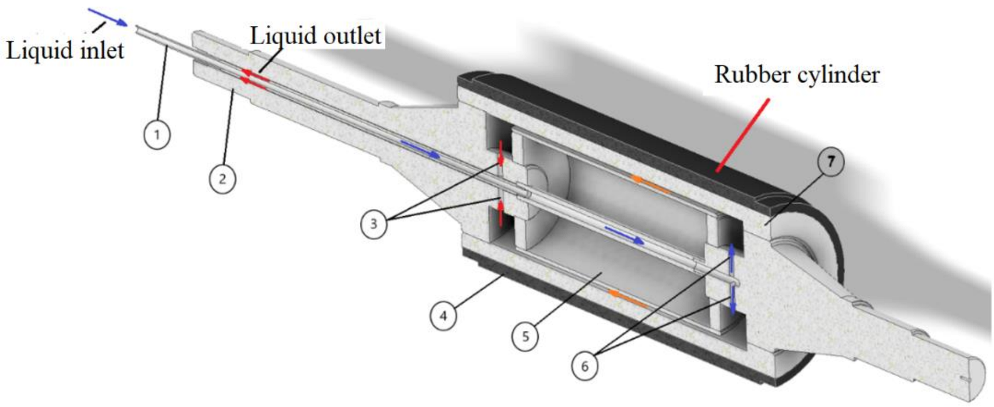

Figure 5. 1) Inlet pipe for the cooling fluid system, 2) Cylinder shaft, 3) Outlet path from the cooling fluid system, 4) Rubber coating, 5) Inner cylinder, 6) Inlet path for the cooling fluid system, 7) Steel cylinder

Table 1. Experimental conditions of the chiller machine

Parameters	Value
Inlet pressure of the cooling fluid system (kPa)	140.0
Cooling fluid flow rate (L/min)	4.1
Operating pressure of the embossing piston (bar)	120.0
Inlet temperature of the cooling liquid (°C)	10.0
Outlet temperature of the cooling liquid (°C)	13.3

2. Results and Discussion

Figure 6 shows the temperature variations on the surface of the natural rubber-coated cylinder, measured in the current system at 350 m/min with an embossing unit featuring the pattern density of Figure 4b. This data includes both cooled and non-cooled conditions. During machine operation, the surface temperature of the rubber cylinder exhibits a near-linear increase over time. Upon reaching a critical temperature of approximately 46 °C, the rubber cylinder experiences damage. As noted in the introduction, numerous factors contribute to the deterioration of rubber cylinders; however, this study specifically investigates the impact of temperature on this phenomenon.

In the experiment with the cooling system applied, as shown in Figure 6, the cooling process commenced at approximately 43 °C. Due to limitations in the circulation capacity of the chiller unit used for circulating the cooling liquid (specifically, the operational capacity of the unit used in the experiment), a cooling liquid flow rate of 4.1 L/min is adopted. Following an initial temperature rise, the temperature gradually decreases. This temperature reduction continues for approximately 90 minutes before stabilizing around 41 °C. Consequently, the surface of the rubber cylinder is maintained at approximately 4-5 °C below the critical temperature threshold, thereby delaying the onset of damage.

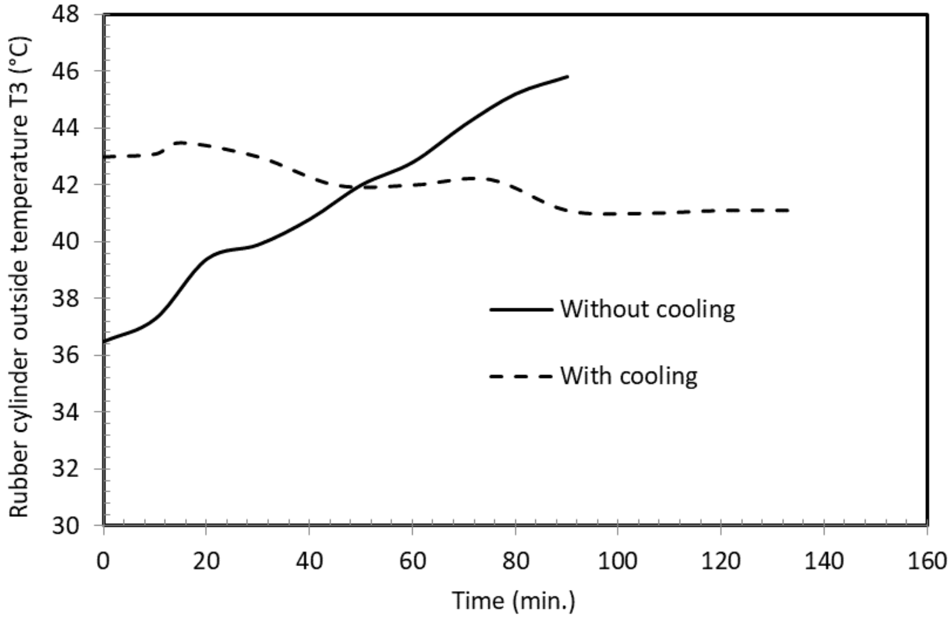

Figure 6. Experimental results at a machine operating speed of 350 m/min with and without cooling

Furthermore, the implemented cooling system not only prevents the rubber cylinder from reaching damaging temperatures but also significantly enhances the overall performance and operational efficiency of the embossing machine. By maintaining the surface temperature within an acceptable range, the cooling system minimizes the risk of premature wear and deformation of the rubber cylinder. Therefore, downtime and production interruptions may be prevented. This highlights the critical role of temperature control in enhancing the reliability and longevity of embossing equipment in tissue paper manufacturing.

In Figure 7, the thermal camera images offer a visual representation of the contrasting temperature profiles of the embossing and rubber cylinders. Firstly, the embossing cylinder maintains a consistently low temperature throughout the observation period. This characteristic thermal behaviour is attributed to its material composition. Typically constructed from steel or other high-conductivity materials, the embossing cylinder possesses a high heat transfer coefficient. This property allows for efficient heat dissipation, keeping the cylinder at a relatively low temperature even under extended operational durations. In contrast, the rubber cylinder exhibits a completely different thermal response, with its temperature escalating to elevated levels. The underlying cause of this temperature increase lies in the dynamic interplay between pressure, material properties, and mechanical action. As both cylinders engage in the embossing process, the longitudinally flexible rubber cylinder experiences repeated compression. This cyclical compression-decompression occurs at a rapid rate, with the rubber cylinder undergoing approximately 400 compressions per minute along the designated line pattern.

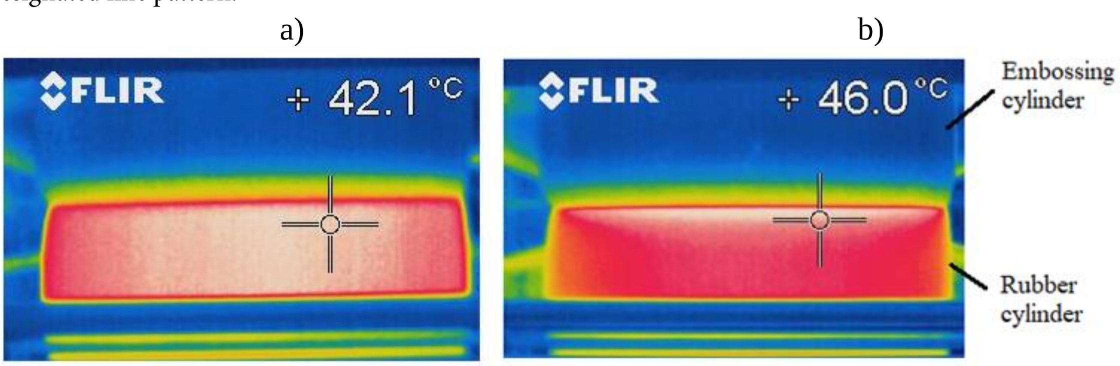

Figure 7. Temperature of the embossing and rubber cylinders during operation. a) Cooling system and b) non-cooling system

The cumulative effect of these compressions is dual. Firstly, repeated mechanical loading induces significant frictional forces within the rubber cylinder, leading to internal energy dissipation and consequent temperature rise. Secondly, the compressive forces generate localized heating within the rubber material, further contributing to its thermal elevation. As a result, the temperature of the rubber cylinder escalates rapidly, forming a sharp contrast with the relatively cool performance of the embossing cylinder. As observed in Figure 7a, the cooling system maintains the rubber cylinder at approximately 4-5 °C cooler temperatures. While the lower heat transfer coefficient of rubber limits the potential for drastic temperature reductions, this modest decrease can significantly extend the cylinder's operational lifespan.

3. Conclusions

This study investigated the use of an internal cooling system to extend the lifespan of the rubber cylinder in a tissue paper embossing machine. A prototype system utilizing a chiller unit was designed, manufactured, and tested. Because of the rubber cylinder's low thermal conductivity and considerable thickness, achieving a substantial cooling effect internally proved challenging. During the experiments, the rubber cylinder starts to damage at a temperature of approximately 46 °C and a speed of 350 m/min, consistent with the specified pattern density. With the implemented cooling system, a cooling of approximately 4-5 °C is attained. Although this 4-5 °C cooling increment helps delay the rubber cylinder's progression to the damage threshold temperature, it remains susceptible to damage at operational temperatures. It is evident that when the machine operating speed is elevated or the pattern density of the paper is increased, the designed system may fall short of providing adequate cooling.

While external cooling may indeed seem like the simplest and ideal approach, certain circumstances may necessitate internal cooling, as demonstrated in this study. Despite the challenges posed by the low thermal conductivity of the rubber cylinder, our research showcases the feasibility of internal cooling for moderate temperature differentials, albeit not without its limitations.

Potential future enhancements and research avenues include the following:

- Employing a chiller unit: a chiller unit capable of operating at lower temperatures and higher flow rates than those employed in the experiments could achieve cooling below 10 °C.
- Redesigning the experimental system: Enhancing heat transfer by refining the contact surface and flow dynamics inside the cylinder could optimize cooling efficiency. This may involve redesigning the cooling system to enhance fluid circulation and maximize contact with the rubber cylinder surface.

Nomenclature

Symbols

A_1	Inner surface area of the steel cylinder (m^2)
A_2	Outer surface area of the rubber coating (m^2)
c_p	Specific heat capacity of the cooling fluid (J/kg.K)
Δt	Temperature difference (°C)
$h_{conv_1,i1}$	Convective heat transfer coefficient for the coolant at the inner surface ($W/m^2.K$)
$h_{conv_2,i2}$	Convective heat transfer coefficient for the air at the outer surface ($W/m^2.K$)
k_{cyl1}	Thermal conductivity of the steel cylinder (W/m·K)
$R_{Cyl.1}$	Thermal resistance, ($K \cdot m^2/W$)
k_{cyl2}	Thermal conductivity of the rubber (W/m·K)
$R_{Cyl.2}$	Thermal resistance ($K \cdot m^2/W$)
M	Mass flow rate of the cooling fluid (kg/s)
Q	Heat transfer rate (W)
r_1	Inner diameter of the steel cylinder (m)
r_2	Outer radius of the steel cylinder (m)
r_3	Outer radius of the rubber coating (m)

$R_{conv_1,i1}$	Convective heat transfer resistance at the inner surface (K·m²/W)
$R_{conv_2,i2}$	Convective heat transfer resistance at the outer surface (K·m²/W)
R_{total}	Total thermal resistance (K·m²/W)
T	Temperature (°C)
$T_{\infty 1}$	Temperature of the cooling fluid or surrounding on the inner side (°C)
$T_{\infty 2}$	Temperature of the air or surrounding on the outer side (°C)

Subscripts

i:	Inner surface
o:	Outer surface
cyl:	Cylinder
conv:	Convection

Conflict of Interest Statement

The authors declare that there is no conflict of interest

References

[1] J. C. Vieira, P. T. Fiadeiro, and A. P. Costa, "Converting Operations Impact on Tissue Paper Product Properties – A Review," *Bioresources*, vol. 18, no. 1, 2023. doi:10.15376/BIORES.18.1.VIEIRA

[2] Y. Chen *et al*., "Parameter optimization of rubber cylinder of expansion liner hanger based on numerical simulation," *Journal of Engineering and Applied Science*, vol. 69, no. 1, pp. 1–18, Dec. 2022. doi:10.1186/S44147-022-00086-4

[3] J. Zhang, M. Sahli, J. C. Gelin, and T. Barrière, "Roll manufacturing of polymer microfluidic devices using a roll embossing process," *Sens Actuators A Phys*, vol. 230, pp. 156–169, Jul. 2015. doi:10.1016/J.SNA.2015.03.002

[4] M. D. Fagan, "A Novel Process for Continuous Thermal Embossing of Large- Area Nanopatterns onto Polymer Films," Masters Theses, University of Massachusetts Amherst, Massachusetts, USA, 2008.

[5] M. D. Fagan and B. H. Kim, "A Novel Process for Continuous Thermal Embossing of Large-Area Nanopatterns onto Polymer Films," *Advances in Polymer Technology*, vol. 28, no. 4, pp. 246–256, 2009. doi:10.1002/adv.20167

[6] W. Ma, H. Yu, Y. Liu, and C. Qian, "Numerical simulation and parameter sensitivity analysis for the cooling of rolling rubber-film on cooling-drums," *J Phys Conf Ser*, vol. 1549, no. 4, p. 042115, 2020. doi:10.1088/1742-6596/1549/4/042115

[7] Y. Deng, P. Yi, L. Peng, X. Lai, and Z. Lin, "Flow behavior of polymers during the roll-to-roll hot embossing process," *Journal of Micromechanics and Microengineering*, vol. 25, no. 6, p. 065004, May 2015. doi:10.1088/0960-1317/25/6/065004

[8] A. Perez, R. R. Van Der Woude, and R. Dekker, "Rotor Cooling Concept for the ASuMED Superconductive Motor," *IOP Conf Ser Mater Sci Eng*, vol. 502, no. 1, p. 012139, Apr. 2019. doi:10.1088/1757-899X/502/1/012139

[9] W. Li, S. Song, Y. Zhai, Y. Zhang, P. Yi, and X. Lai, "Rheological behavior of ethylene–vinyl acetate copolymer and fabrication of micropyramid arrays by roll-to-roll hot embossing on its thin films," *J Appl Polym Sci*, vol. 134, no. 34, pp. 1–9, 2017. doi:10.1002/app.45228

[10] W. Li, Y. Zhai, P. Yi, and Y. Zhang, "Fabrication of micro-pyramid arrays on PETG films by roll-to-roll hot embossing," *Microelectron Eng*, vol. 164, pp. 100–107, 2016. doi:10.1016/j.mee.2016.08.001

[11] J. C. Vieira *et al*., "Embossing Lines and Dots Geometry Effect on the Key Tissue Paper Properties with Finite Element Method Analysis," *Polymers 2022, Vol. 14, Page 3448*, vol. 14, no. 17, p. 3448, Aug. 2022. doi: 10.3390/POLYM14173448

[12] A. M. Morega, I. Dobrin, M. Popescu, and M. Morega, "Heat transfer analysis in the design phase of a high temperature superconductor motor," in *Proceedings of the 12th International Conference on Optimisation of Electrical and Electronic Equipment, OPTIM*, pp. 401–406, 2010. doi:10.1109/OPTIM.2010.5510528

[13] S. Kim, Y. Son, H. Park, B. Kim, and D. Yun, "Effects of Preheating and Cooling Durations on Roll-to-Roll Hot Embossing," *Microscopy and Microanalysis*, vol. 21, no. 1, pp. 164–171, Feb. 2015. doi:10.1017/S1431927614013324

[14] J. Liu, H. Chen, S. Huang, Y. Jiao, and M. Chen, "Recent Progress and Prospects in Liquid Cooling Thermal Management System for Lithium-Ion Batteries," *Batteries 2023, Vol. 9, Page 400*, vol. 9, no. 8, p. 400, Aug. 2023. doi:10.3390/BATTERIES9080400

[15] J. Zhang, X. Jia, and Q. He, "Mechanical, thermal, and friction properties of addition-type fluororubber co-filled with Al2O3 particles at high temperature," *Polym Test*, vol. 96, p. 107131, Apr. 2021. doi:10.1016/J.POLYMERTESTING.2021.107131