

Article

Numerical Simulation on Ink Transfer Channel of Flexography Based on Fluid–Solid–Heat Interactions

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Abstract: Flexographic printing is widely used in the packaging field, but there are still some problems in the printing of flexographic ink on non-absorbent substrates, such as low precision and unstable quality. In this paper, the printing process of flexographic ink is simulated. The interaction of fluid flow, temperature change, and solid deformation in flexographic printing is studied systematically by using the method of fluid–solid thermal coupling for the first time. The process of ink channel formation under static extrusion and fluid–solid thermal coupling was analyzed. The influences of printing pressure, printing speed, ink layer thickness, and ink viscosity on the ink channel were explored. The results show that the printing speed increases and the temperature in the stamping area increases. The printing speed is nonlinear related to the ink flow channel, the influence on the channel is slow at a low speed, the channel increases sharply at a medium and high speed, and tends to be stable at a high speed. When the printing speed is 200 m/min, the ink temperature in the stamping area is 1.5 °C higher than that at the entrance. With an increase in printing pressure, the ink flow channel width showed a trend of decreasing first and then stabilizing, and the pressure was about 0.4 MPa, showing a small fluctuation; the greater the pressure, the higher the temperature of the ink, which will change the performance of the ink and plate, causing adverse effects on the printing belt. The channel width showed obvious nonlinear characteristics with an increase and decrease in ink thickness. When the ink thickness is 30 µm, the deformation of the plate reaches the maximum, and the width of the ink circulation channel is correspondingly the widest. The change in ink viscosity has little influence on the stability of the ink's internal flow rate and temperature field. The research results provide theoretical support for the transfer of ink printing from gravure to flexo printing.

Keywords: flexography; ink channel; ink transfer; statics analysis; fluid–solid thermal coupling



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1. Introduction

Flexography has been widely used in the field of packaging printing for its high efficiency, strong adaptability, and wide range of printing materials. Its combination with the printing and electronic industry gives full play to the unique advantages of flexo printing and promotes the good development of the printing and electronic industry [1,2]. However, with the increasing demand for printing quality and efficiency in the market, further understanding and optimization of the flexographic printing process has become increasingly important [3]. Scholars all over the world have paid much attention to flexographic printing and have deeply studied various aspects of flexographic printing technology [4–7]. In view of the complexity and difficulty of the printing mechanism of non-absorbent substrates in gravure printing, Wu Shuang, Dong Ling, Guan Xiaomin, and Zhu Hongjuan have made a preliminary study on the transfer and drying of gravure water-based ink [8–11]. The research results provide a way to solve the problem of gravure flexo printing on a non-absorbent substrate. In the field of ink transfer, Zhang successfully simulated the

formation and fracture of droplets by Volume of Fluid (VOF) and further revealed the transfer mechanism of liquid [12]. Since then, Huang and other researchers have also used the VOF method to simulate the fluid transfer between a trapezoidal cavity and substrate by changing the contact angle, initial interval, and cavity shape and analyzing the fluid transfer from the trapezoidal cavity to the upper plate under different conditions [13,14]. The results showed that the forming process of liquid transfer can be divided into three stages, from the whole drawing to the middle stretching, cracking and recoil, and then to the final equilibrium stage. The ink width on a substrate is affected by ink wettability, and the position of wire breakage is related to the contact angle formed by the inner wall of the liquid and mesh. Anjun [15] studied the effect of the printing substrate, printing plate, ink used, and screen roller specification on ink transfer and then discussed the effect of each process parameter on the quality of the printed matter. Researchers such as Chen Jiaxiang analyzed the characteristics of ink transfer from the mesh roller to the printing plate. The results showed that the ink transfer rate decreased with an increase in the contact angle of the upper plate and increased with an increase in the contact angle of the trapezoidal groove. The smaller the aspect ratio of the trapezoidal groove and the larger the angular velocity, the higher the ink transfer rate [16]. Therefore, the corresponding anilox roller can be selected to optimize the printing quality. Zhang Lin [17] established a prediction model of flexographic printing quality by using a multiple linear regression equation and finite element analysis and discussed the influence of the process parameters of a roller, inking system accessories, ink specification, printing plate elastic modulus, and printing speed on printing quality. Liu [18] established the ink-transfer unit model of printing ink from the roller to plate in flexo printing and used simulation software to control a single variable to simulate the process parameters such as speed, roller parameters, viscosity, pressure, and so on. Therefore, the research on ink transfer in flexographic printing mostly focuses on the influence of printing species, plate material, pressure, and other factors on ink transfer, or uses simulation software to simulate the ink transfer process, and summarizes the influence of printing substrate characteristics, pressure, speed, and ink transfer, but there is no study on the interaction among the plate cylinder, ink, and impression cylinder, and there is no report on thermal stress research. Therefore, this paper introduces the fluid–structure coupling thermal stress method to analyze the flexographic printing system and uses the finite element method to explore the formation of the ink flow channel and the influence of printing parameters on the ink channel.

As shown in Figure 1, firstly, the water-based ink with low viscosity and high fluidity is filled into the screen hole of the roller by the cavity-type ink scraping system, and then the ink carried by the roller is contacted with the printing plate to transfer the ink to the printing plate roller; then, the printing plate contacts with the surface of the substrate to transfer the attached ink to the substrate and complete the ink transfer; finally, the substrate bearing the ink is output after the drying system to complete the printing process.

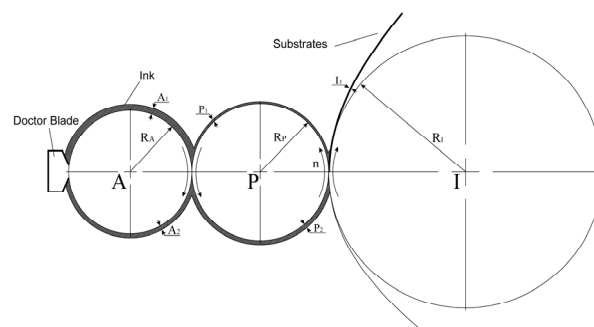


Figure 1. Principle of ink transfer in flexographic printing.

In the picture, A is the anilox roller, P is the plate cylinder, I is the impression cylinder, R_A , R_P , and R_I are the radii of the three rollers respectively. A_1 is the initial ink thickness,

A2 is the ink thickness on the surface of the anilox roller after ink transfer, P1 is the ink thickness on the surface of the plate cylinder after ink transfer, P2 is the ink thickness on the surface of the plate cylinder before ink transfer, and I1 is the ink thickness on the surface of the product after ink transfer.

The ink transfer process can be divided into three stages; this paper focuses on the third stage, that is, ink transfer to the substrate through the relative motion of the plate cylinder and impression cylinder. In this paper, the intrinsic mechanism of the ink transfer process is discussed, including the ink fluid, the elastic plate, and the solid metal roller. The heat transfer effect between them is analyzed.

2. Materials and Methods

Fluid–solid coupling thermal stress widely exists in mechanical, power, energy, aerospace, chemical, and nuclear engineering fields [19–23]. On one hand, it refers to the interaction between the fluid and the heat transfer process through the displacement, deformation, heat transfer, and phase change of the fluid–solid interface. On the other hand, it also refers to the coupling of different physical processes, such as flow and radiation, at the interface.

Due to the complexity of flexographic printing in the embossing process, the following assumptions are made to simplify the model: ignoring the information on the printing plate surface, ignoring the influence of gravity, ignoring the thickness of the substrate, and assuming that water-based ink is a uniformly distributed substance, ignoring the influence of solid phases in the ink composition (such as pigments and dyestuffs) in the flow.

2.1. Governing Equations of Fluid Mechanics

In this study, the flow pattern of ink fluid is incompressible flow. The motion characteristics of viscous incompressible fluids are generally described by the Navier–Stokes equation. The continuity and momentum equations are given as follows [24]:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\begin{cases} \frac{\partial \rho u}{\partial t} + \text{div}(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x \\ \frac{\partial \rho v}{\partial t} + \text{div}(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y \\ \frac{\partial \rho w}{\partial t} + \text{div}(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + F_z \end{cases} \quad (2)$$

Among them, ∇ is the Hamiltonian differential operator, ρ is the fluid density, $\mathbf{u}$ is the velocity vector, p is the pressure on the fluid unit, τ_{xx} , τ_{xy} , and τ_{xz} are the viscous stress on the surface of the fluid unit, and F_x , F_y , and F_z are the volume force on the fluid unit.

2.2. Solid Governing Equation

As a kind of nonlinear elastic solid material, six basic strain components can be used to describe the deformation of any position in the nonlinear elastic body. The equations are expressed as follows:

$$\begin{cases} \varepsilon_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial x} \right)^2 \right] \\ \varepsilon_{yy} = \frac{\partial v}{\partial y} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial y} \right)^2 \right] \\ \varepsilon_{zz} = \frac{\partial w}{\partial z} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right] \\ \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial v}{\partial y} + \frac{\partial w}{\partial x} \frac{\partial w}{\partial y} \\ \gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} + \frac{\partial u}{\partial z} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial z} \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \frac{\partial w}{\partial y} \\ \gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} + \frac{\partial u}{\partial x} \frac{\partial u}{\partial z} + \frac{\partial v}{\partial x} \frac{\partial v}{\partial z} + \frac{\partial w}{\partial x} \frac{\partial w}{\partial z} \end{cases} \quad (3)$$

When the elastic deformable body deforms greatly under the action of external forces, the balance of external forces and internal forces on the body is very complicated [25,26]. Establishing a Cartesian rectangular coordinate system, (x, y, z) , to indicate the position of the center of gravity, the equation of the balance of forces is as follows:

$$\begin{cases} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x = 0 \\ \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} + F_y = 0 \\ \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + F_z = 0 \end{cases} \quad (4)$$

Among them, σ_x , σ_y , and σ_z represent the corresponding normal stress, respectively, τ_{xy} , τ_{yz} , and τ_{zx} represent the corresponding shear stress, respectively, and F_x , F_y , and F_z represent the forces in the corresponding direction, respectively.

The stress–strain relationships of the materials are as follows [23]:

$$\sigma_{ij} = \frac{E}{1+v} \varepsilon_{ij} + \frac{vE}{(1+v)(1-2v)} \theta \delta_{ij} \quad (5)$$

E is the elastic modulus, v is the Poisson's ratio, and θ is the first strain invariant.

2.3. Heat Transfer Analysis

Heat is generated by friction between the flexographic plate and ink during ink transfer. How to determine the heat distribution of ink between two rollers and how to realize heat transfer is the key problem of heat transfer.

According to the principle of the conservation of energy, it is used to describe the flow of heat from a high-temperature region to a low-temperature region. The convective heat transfer equation can be expressed as follows [27]:

$$\rho \frac{d}{dt} \left(H + \frac{1}{2} v^2 \right) - \frac{\partial p}{\partial t} = 0 \quad (6)$$

So, ρ is density, H is enthalpy, v is velocity, and p is pressure.

From the conservation of energy, we know that at the fluid–solid coupled thermal stress interface, the heat transferred by a solid should be equal to the heat absorbed by the fluid [28]. Thus, the heat transfer process at the fluid–solid interface can be expressed as follows:

$$\lambda \left(\frac{\partial T}{\partial x} \right) = \alpha (T_w - T_f) \quad (7)$$

α is the convective heat transfer coefficient, T_w is the solid wall temperature, and T_f is the fluid temperature.

Based on the above research methods, and firstly, based on the finite element numerical method, the fluid model and solid structure model of the ink are established according to the physical characteristics of the printing process. After the model is built, the region grid is divided carefully. The quality of the grid directly affects the accuracy of the calculation results and the efficiency of the calculation process. At this stage, the mesh of the complex geometric regions needs to be optimized to accommodate the detailed characteristics of fluid flows and solid structures. In order to improve the grid quality and avoid the influence of the grid number on the calculation result, it is necessary to verify the independence of the grid number. In this study, different grid numbers were selected to investigate the temperature of the ink fluid entering the printing pressure zone to ensure that the relative tolerance of the simulation was small. The result is shown in Figure 2. It can be seen that when the number of grids exceeds 600,000, the simulation results do not change much. In order to ensure calculation accuracy and reduce the calculation time as much as possible, 600,000 grids are adopted in this paper. Since the ink fluid is attached to the surface of the plate cylinder and rotates with the plate cylinder, the inner wall of the ink fluid is set to the

rotating wall without slip, the speed is 160 m/min, the thermal boundary condition of the wall is heat convection, and the front and back end faces are set to the symmetric boundary. The inlet is the pressure inlet, and the pressure is 0 Mpa. Then, the fluid simulation is performed. The stress distribution and deformation of the solid structure are analyzed by introducing the calculation results into the solid module. Finally, the post-processing software CFD-Post only 2020 R2. was used to integrate and analyze the results, evaluate the effect of the interaction between the ink flow and solid under different simulation conditions, and extract key performance indicators and image data for the optimization of flexographic printing process technology to provide a scientific basis. The software used in this study was provided by ANSYS, Inc., 2600 ANSYS Drive, Canonsburg, PA 15317, USA.

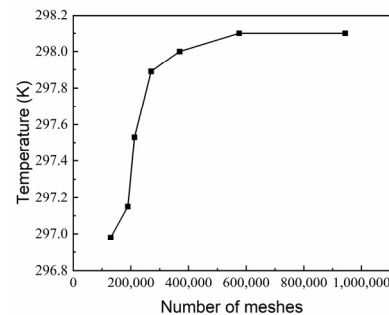


Figure 2. Verification of grid independence.

3. Statics Analysis

This study is based on the structural parameters of a flexographic printer; the static simulation was carried out in ANSYS (2020 R2) software using the Static Structure module to determine the deformation of the flexographic press under different press pressures. The plate cylinder radius R_p is 100 mm, and the impression cylinder radius R_i is 200 mm. The impression cylinder material is structural steel, the elastic modulus E_i is 2.09 GPa, the Poisson's ratio ν_i is 0.269, and the density ρ is 7890 kg/m³. The flexo plate is made up of an inner steel core and a photosensitive resin plate. Because the elastic modulus of the inner steel roll is much larger than that of the resin plate, the inner steel roll will hardly deform. The flexible plate thickness is 1.14 mm, the density is 1200 kg/m³, the elastic modulus is 2.72 GPa, and the Poisson's ratio is 0.316. Statics is mainly concerned with the static effects of materials and structures under fixed loads, that is, without considering inertia and damping. In this case, the primary concern is the stress, strain, and stability of materials and structures in static equilibrium without ink. The flexo printing process is especially for non-absorbent substrate printing, and because the substrate deformation is very small, we ignore the impact of the substrate. Therefore, the static compression deformation of the substrate is not considered, the flexible resin plate is mainly studied [20], and the printing pressure is mainly considered. In order to reduce the computational cost, the simplified model makes the analysis more efficient and can accurately predict the mechanical deformation in the flexo printing process, which can provide a theoretical reference for engineering design. Figure 3 shows a two-roll extrusion model. The symbols in the figure are the same as above, d is the thickness of the flexographic plate, F is the printing pressure, and λ is the shape variable of the two-roll extrusion flexographic plate.

In the ANSYS Static Structure module, the deformation of flexo under printing pressure can be simulated by defining boundary conditions and applying pressure loads. In order to simulate the extrusion of the flexo plate in the printing process, the press roller is used to exert force on the flexo plate while keeping other parameters unchanged. In this way, the deformation cloud and the average deformation can be obtained. Under the action of the impression cylinder, in the contact area between the flexo plate and the impression cylinder occurs extrusion deformation. The extruded flexo plate will be extruded to both sides, resulting in the maximum deformation in the center of the contact area, and then

gradually reduced. This is because the maximum pressure is at the center of contact. With an increase in the distance from the center, the pressure and the deformation decrease.

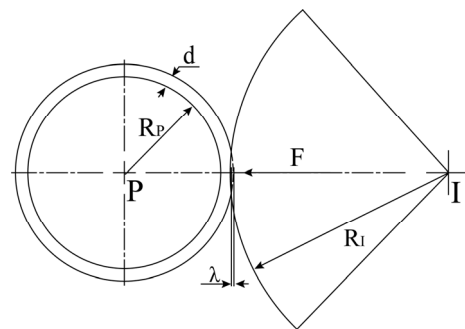


Figure 3. Static extrusion model.

Figure 4 shows the average deformation data under different printing pressures (between 0.1 and 0.5 MPa). It can be seen from the figure that the relationship between the printing pressure and the printing center shape variable is basically linear. With an increase in printing pressure, as a kind of viscoelastic material, the flexible photosensitive resin plate will become more complicated. When the external force acts on the flexographic plate, the external force does work on the flexographic plate, converting part of the energy into internal energy, resulting in changes in the molecular structure inside the photosensitive resin plate and generating heat. In the printing process, the contact center of the two rollers is concentrated here, the stress reaches the maximum value, and the stored strain energy is the maximum. So, we can speculate on a temperature rise here. The results of static simulation are of great significance to understand the mechanical behavior and deformation of the flexographic printing process and to optimize printing equipment and process parameters. In this paper, the fluid–solid coupled thermal stress simulation of the ink transfer process is studied. In this paper, we will simulate the fluid–solid coupling thermal stress of the ink transfer process in the two-roller imprint area.

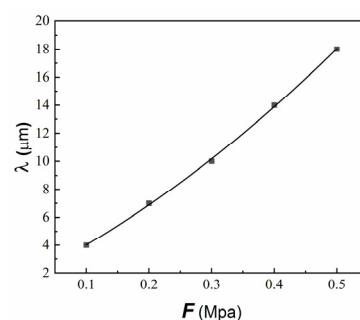


Figure 4. Fitting curve of printing pressure and flexographic shape variable.

4. Analysis of Flow, Solid, and Heat Coupling on Ink Transfer Channel

As shown in Figure 5, as the printing plate and the impression roller rotate and extrude, the ink on the printing plate surface will be transferred to the surface of the impression roller (namely the substrate). Under the combined action of the flow field pressure and thermal stress of the ink, the plate will be deformed, and the gap between the printing plate cylinder and the impression roller, which are originally in close contact, will be formed due to the ink extrusion, forming the ink circulation channel. The symbol interpretation in the figure is the same as above, n is the printing speed, s is the width of the ink channel. The formation of this flow passage is influenced by mechanical mechanics, fluid dynamics, and thermodynamics. In the process of ink transfer, there is a complex interaction between the flow field and solid material, which further affects the plate deformation and ink flow characteristics.

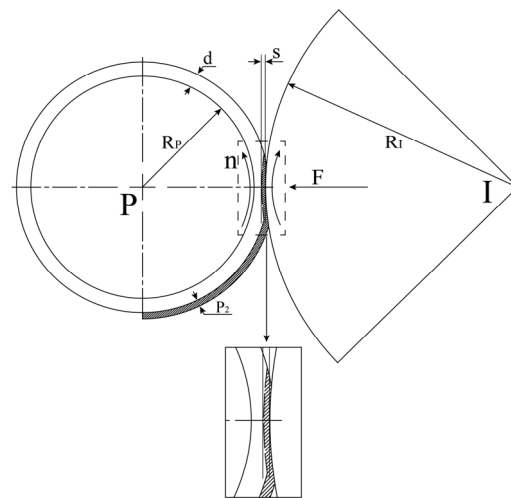


Figure 5. Inking channel formation schematic.

In order to analyze the width of the ink flow channel in the flexo printing process, the fluid and solid model of water-based ink entering between two rollers was established in the ANSYS 2020 R2 simulation software. The simulation of the ink channel with different printing process parameters was carried out by using the method of fluid–solid–heat coupling. In the simulation stage, because the deformation of the impression roller has little effect on the whole process, the model only includes the ink layer and flexography. The density of the water-based ink used in this paper is 1012.93 kg/m^3 , the specific heat capacity is $2500 \text{ J/(kg}\cdot\text{K)}$, the thermal conductivity is $0.4 \text{ W/(m}\cdot\text{K)}$, and the viscosity is $0.4 \text{ Pa}\cdot\text{s}$. In addition, in order to optimize the computational resources, only the local model of the ink fluid was established in the key areas. This method can not only improve the calculation efficiency of the model but also accurately predict the ink flow behavior under different printing conditions.

5. Results

5.1. Influence of Printing Speed on Ink Flow Channel

5.1.1. Ink Channel Changes with Printing Speed

The ink in the transfer process is in a laminar flow state. In order to obtain the ink flow channel width at different printing speeds, the fluid–solid thermal coupling experiment was carried out under the conditions of an ink layer thickness of $P_2 = 30 \text{ }\mu\text{m}$ and a printing pressure of $F = 0.4 \text{ MPa}$. The variation trend of the printing speed and ink channel width is fitted by polynomials, as shown in Figure 6. The results show that when the printing speed is less than 150 m/min , with an increase in the printing speed, the change range of the ink flow channel width is less than $4 \text{ }\mu\text{m}$. When the printing speed is greater than 150 m/min , with an increase in the printing speed, the ink flow channel width suddenly becomes larger, from $4.13 \text{ }\mu\text{m}$ to $6.01 \text{ }\mu\text{m}$. When approaching 200 m/min , the channel width changes gently, and the channel width is $7.5 \text{ }\mu\text{m}$. It shows that the printing speed is nonlinear related to the ink flow channel, the influence on the channel is relatively slow at a low speed, the channel increases sharply during a middle and high speed, and tends to be stable at a high speed. The change trend of this study is the same as that of Guan et al., which verifies the rationality of the results [10,18]. Corresponding to the speed and channel width value in actual work, it is ideal to select the working state in the middle area of $140\text{--}180 \text{ m/min}$. If the speed is too low, the channel is too narrow, and if the speed is too high, the channel is too wide, which will affect the printing quality. In order to explore the specific influencing factors of printing speed on the ink flow channel, the fluid velocity cloud image, pressure cloud image, and temperature cloud image under different printing speeds were selected to analyze.

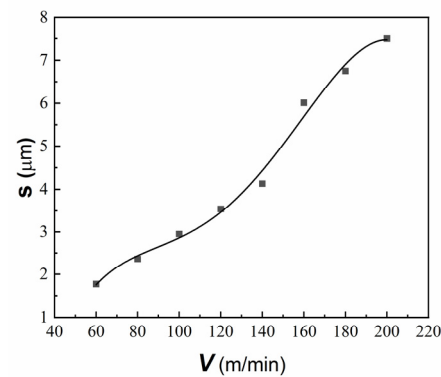
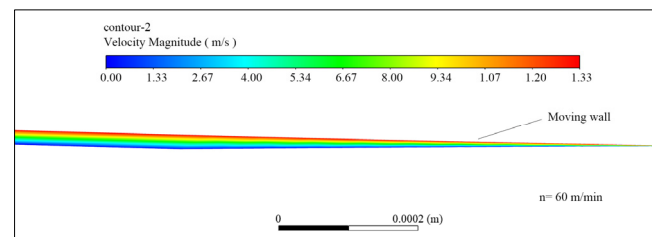
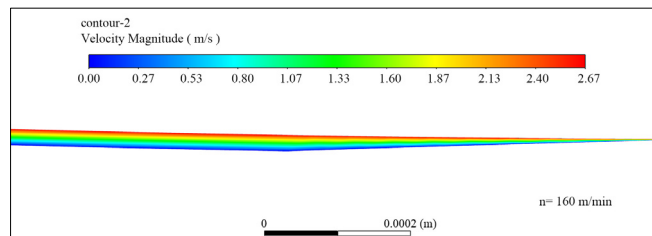


Figure 6. The ink channel fits the curve with a change in printing speed.

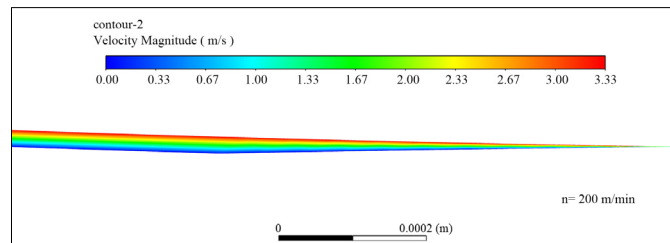
As can be seen from Figure 7, the ink flow rate near the plate cylinder wall is higher, and the flow rate away from the wall is lower. This speed distribution may be caused by the ink being subjected to shear force on the surface of the drum. When printing at a high speed, the shear force is greater, resulting in faster ink flow near the contact surface. This uneven flow velocity distribution may affect the uniformity of the ink layer, which in turn affects the sharpness and color saturation of the image.



(a)



(b)



(c)

Figure 7. Fluid velocity distribution at different printing speeds. (a) $n = 60$ m/min; (b) $n = 160$ m/min; (c) $n = 200$ m/min.

5.1.2. Thermal-Stress Analysis

The results shown in Figures 8 and 9 show that in the process of high-speed printing, the influence of flow field pressure and thermal stress on the pressure zone in the center

of the cylinder increases significantly. When the printing speed increases by 40 m/min, the maximum ink temperature rises by 0.3 °C. When the printing speed is 100 m/min, the maximum temperature is 296.7 K (23.55 °C), which is 0.7 °C different from the temperature of the ink at the entrance. When the printing speed is 200 m/min, the maximum temperature is 297.5 K (24.35 °C), which is 1.5 °C different from the temperature of the ink at the entrance.

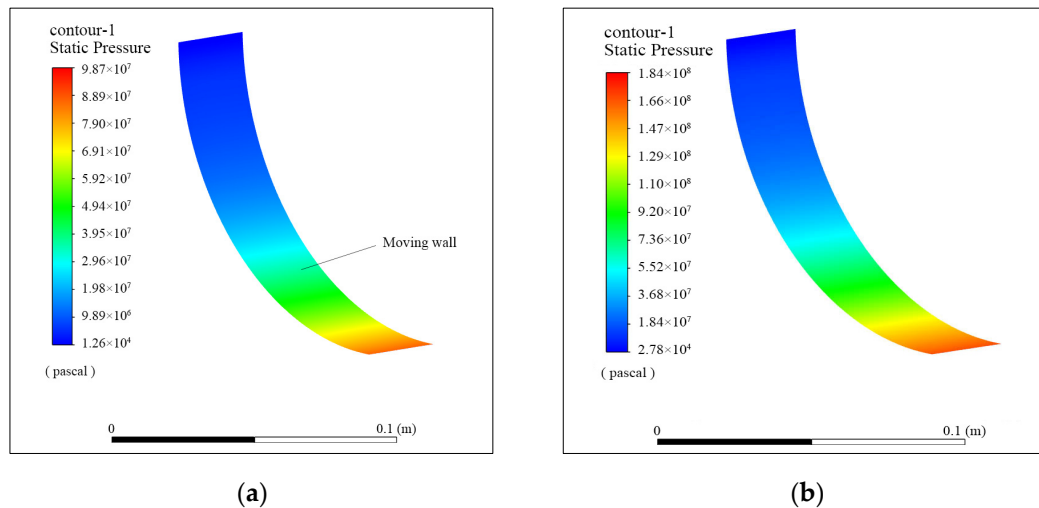


Figure 8. Fluid pressure distribution at different printing speeds. (a) $n = 120$ m/min; (b) $n = 200$ m/min.

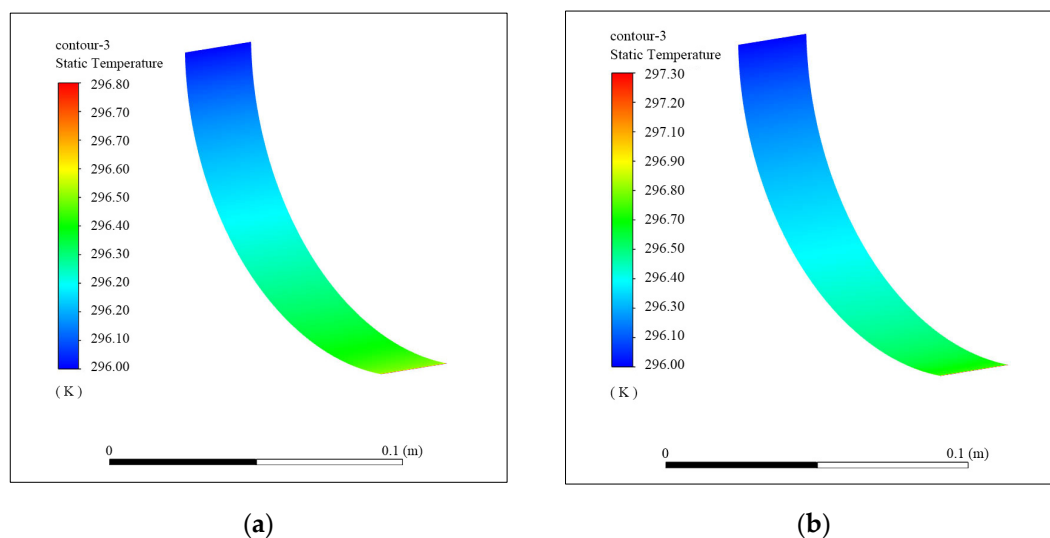


Figure 9. Cloud image of fluid temperature at different printing speeds. (a) $n = 120$ m/min; (b) $n = 200$ m/min.

The following conclusions can be drawn: during the printing process, especially in the printing impression area, the contact between the drum and the ink and the plate will produce friction. As the printing speed increases, friction increases, causing more energy to be converted into heat. This phenomenon is particularly evident in the printing impression area, where the ink is transferred to the substrate and the pressure between the rollers is greatest.

The heat generated by friction will not only locally heat the plate and the embossing cylinder but also affect the temperature of the ink through heat conduction and convection. The physical properties of the ink at high temperatures, such as viscosity and surface tension, will change. Usually, the viscosity of the ink decreases with an increase in temperature,

which may cause the ink to transfer more easily from the plate to the substrate, but at the same time, it may cause the ink to splash or spread, affecting the printing quality.

It can be seen that a long time of high-speed printing will cause the printing machine itself to overheat, which will affect its mechanical properties and lifetime. For example, the printing drum and other parts may undergo thermal expansion due to excessive temperature, which will affect the printing accuracy. The increase in printing speed causes the temperature of the printing impression area to rise, which not only affects the physical and chemical properties of the ink but also may affect the printing quality and the operational performance of the equipment. Therefore, in the actual printing operation, it is crucial to reasonably control the printing speed and related temperature management strategies. For example, a water cooling system was used to pass circulating cooling water through the inside of the drum, so as to achieve heat exchange control of the external wall temperature [29–31], so as to ensure high-quality printing output and stable operation of the equipment.

5.2. Influence of Printing Pressure on Ink Flow Channel

5.2.1. Ink Channel Changes with Printing Pressure

Under different printing pressures, the thickness of the ink layer was 30 μm and the printing speed was 180 m/min. The cloud pattern of the ink layer velocity was similar to that of Figure 6, and the internal flow field velocity did not change significantly, indicating that the change in the printing pressure would not change the flow velocity state of the fluid. The fluid channel changes significantly, as shown in Figure 10. When the printing pressure increased from 0.1 Mpa to 0.3 Mpa, the width of the fluid channel narrowed rapidly, and the decrease was obvious, and then during the period of 0.3 Mpa–0.5 Mpa, the channel width fluctuated slightly, and the change range was not large, indicating that the printing pressure value in this range was reasonable.

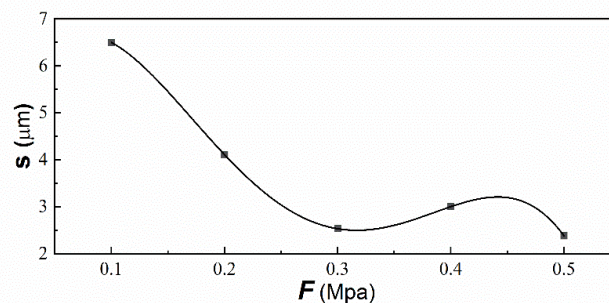


Figure 10. Ink channel changes with printing pressure.

5.2.2. Analysis of Flow Field Pressure and Temperature Field under Different Pressures

In order to describe the channel variation phenomenon, the fluid pressure and temperature cloud maps of Figure 11 were further analyzed. With an increase in printing pressure, the flow field pressure increases gradually. This can lead to compression of the ink flow channel because greater pressure will limit the ink flow space; at the same time, the temperature of the flow field also increases to a certain extent. When the printing pressure is 0.1 MPa, the maximum temperature of the ink is 296.8 K (23.65 °C), which is 0.8 °C higher than the inlet temperature; when the printing pressure is 0.5 MPa, the maximum temperature of the ink is 297.5 K (24.35 °C), 1.5 °C higher than the inlet temperature. Within a certain range, the increase in temperature may cause the thermal expansion of the ink, thereby increasing the width of the circulation channel. Therefore, the interaction of fluid pressure and temperature is an important reason for the change in ink channel width. After 0.3 Mpa, the interaction between the pressure and temperature of the flow field reaches a balance, making the width of the ink flow channel change stable. Obviously, the value of the printing pressure should be in a reasonable area; otherwise, it will bring

inconvenience to printing. At the same time, the use of an imprinting cylinder water cooling cycle is a good choice.

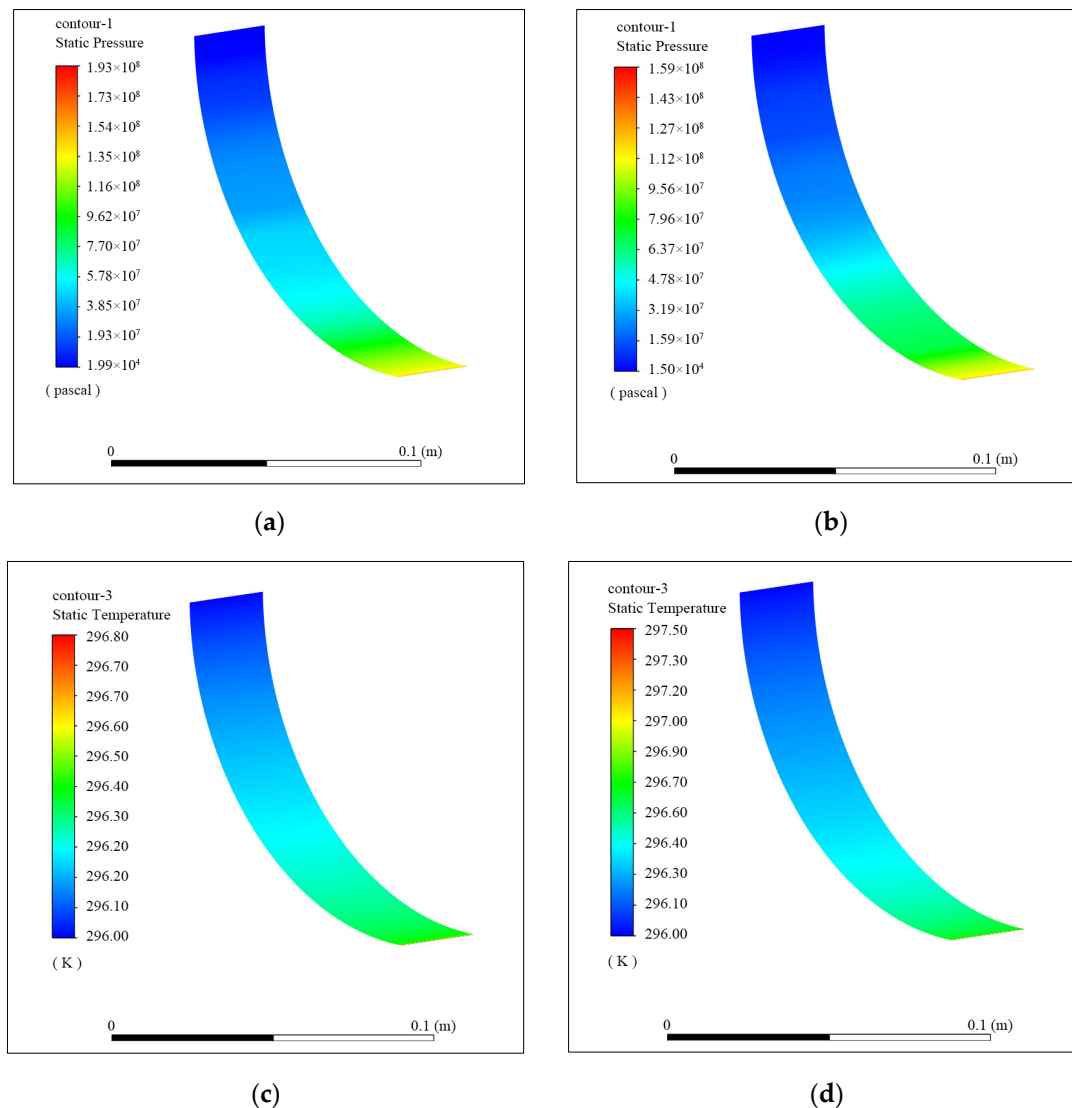


Figure 11. Cloud image of fluid pressure and temperature at different printing pressures. (a) Flow field pressure cloud image at 0.1 Mpa; (b) flow field pressure cloud image at 0.5 Mpa; (c) temperature cloud image of flow field at 0.1 Mpa; (d) temperature cloud image of flow field at 0.5 Mpa.

5.3. Influence of Ink Viscosity and Ink Layer Thickness on Ink Flow Channel

The above research discussed the influence of parameter change of printing equipment on the ink flow channel. Next, based on the characteristics of the ink itself, especially the changes in ink viscosity and ink layer thickness, we assess how these factors affect the ink flow channel. This analysis will help to better understand the rheological properties of ink and its behavior under different printing conditions, and then provide a theoretical basis and practical guidance for the optimization of the printing process.

In order to obtain the ink flow channel width under different ink viscosity and ink layer thickness, under the conditions of a printing pressure of $F = 0.40$ MPa, a printing speed of 180 m/min, an ink viscosity range of 0.1–0.5 Pa·s, and an ink layer thickness range of 20–40 μm , fluid–structure coupling thermal stress simulation experiments were carried out. As shown in Figure 12, it can be seen that the ink channel increases with an increase in ink viscosity; the ink layer thickness near a 30 μm ink channel width reaches the maximum.

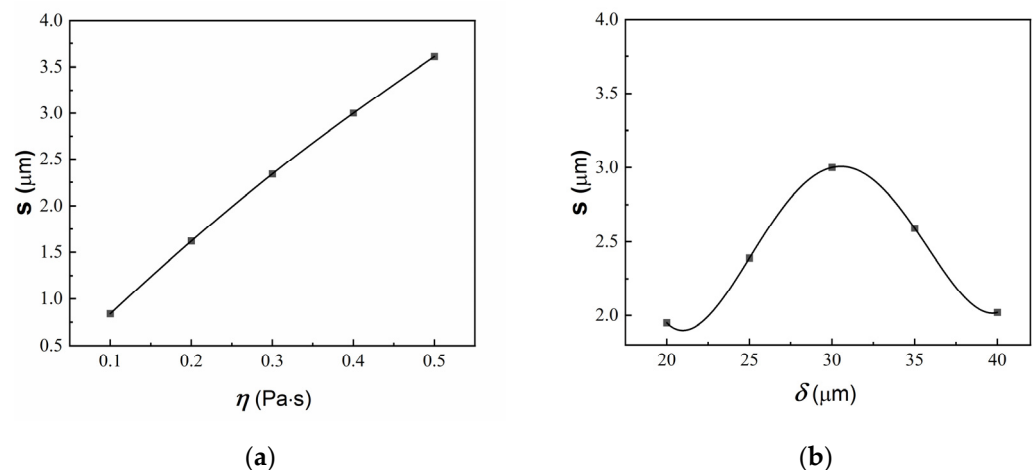


Figure 12. (a) The fitting curve of different ink viscosity and ink flow channel changes; (b) the curve of different ink thickness and ink flow channel change is fitted.

5.3.1. Analysis of Ink Flow Channel under Different Ink Viscosity

According to the velocity and temperature distribution of the flow field, it can be found that the change in ink viscosity does not cause significant changes in the internal flow rate and temperature of the ink fluid, and it is maintained in a relatively stable state. The reason may be that the water-based ink used in this paper is a low-viscosity fluid, and the internal friction is small, so the viscous force is small. Viscous force in fluid mechanics is the force generated by friction between fluid molecules. When a fluid flows, there will be speed differences between different layers of the fluid, which causes the fluid layers to rub against each other and produce resistance. The size of the viscous force depends on the viscosity of the fluid. The higher the viscosity, the greater the viscous force of the fluid. High-viscosity fluids show greater internal friction when they flow. Although ink viscosity is an important parameter that affects fluid flow [32], in some cases, especially when ink viscosity changes are not extreme, the effect of slight changes in viscosity on the flow rate and temperature may not be sufficient to cause significant differences.

5.3.2. Analysis of Ink Flow Channel under Different Ink Thickness

For an ink layer thickness near 30 μm , the ink channel reaches its maximum, probably because the plate roller will produce different degrees of mechanical stress and corresponding deformation when subjected to the pressure of an ink layer of different thickness. When the thickness of the ink layer increases, the surface load on the plate roller increases, resulting in increased drum deformation. Within a certain range, this deformation can increase the width of the ink flow channel. However, when the thickness of the ink layer reaches or exceeds 30 μm , the deformation may hit a limit of structural stability, at which point the deformation of the drum may begin to negatively affect the expansion of the channel so that the channel width decreases with a further increase in the thickness of the ink layer.

6. Conclusions

In order to promote the trend of “gravure transfer flexo printing”, the flexo printing process is simulated and analyzed in this paper. The interaction of fluid flow, temperature change, and solid deformation in flexo printing was studied systematically by using the method of fluid–solid thermal coupling. The channel-forming process of ink in the static extrusion stage was analyzed. The influence of the parameters on the width of the ink circulation channel was discussed. The following conclusions were reached.

With an increase in printing speed, the ink temperature in the printing stamping area will also rise, resulting in the thermal expansion of the ink and a change in fluidity, which will affect the width of the ink circulation channel. The printing speed is nonlinearly related

to the ink flow channel, the influence on the channel is relatively slow at a low speed, the channel increases sharply during a middle and high speed, and tends to be stable at a high speed. With an increase in printing pressure, the width of the ink flow channel shows a trend of decreasing first and then stabilizing, and when the pressure is about 0.4 MPa, it shows a small fluctuation. Similarly, the change in pressure will also cause a change in the ink temperature field; the greater the pressure, the higher the temperature, so that the ink and plate performance changes, bringing trouble to printing. The channel width showed obvious nonlinear characteristics with an increase and decrease in ink thickness. When the thickness of the ink layer is less than 30 μm , the ink flow channel becomes larger with an increase in the thickness. When the ink thickness is 30 μm , the deformation of the plate reaches the maximum, and the width of the ink circulation channel is correspondingly the widest. When the thickness exceeds 30 μm , the channel becomes smaller gradually. The change in ink viscosity has little influence on the stability of the ink's internal flow rate and temperature field.

In summary, the optimization of the printing process requires comprehensive consideration of the interaction of the printing pressure, printing speed, ink thickness, and ink viscosity parameters. By precisely controlling these parameters, the state of the ink flow channel can be significantly improved, and the printing quality and efficiency can be improved. In particular, the printing pressure and printing speed have the most significant impact on the ink flow channel, which needs to be paid attention to in the actual printing process. The change in the ink temperature field caused by the change in printing pressure and printing speed, and the longer time, may cause plate deformation; optimizing the size of the ink channel can improve the printing efficiency and quality, but it needs to be carried out under the premise of ensuring the stability of the plate material and the accuracy of the equipment. Reasonable control of printing pressure and ink thickness, and optimizing the ink flow channel in the dynamic balance state, help to achieve more stable printing quality and higher production efficiency.

This study provides a scientific basis for parameter selection and the process control of the waterborne ink flexo printing process, which is helpful in realizing fine printing process management and quality control in actual production.

Due to the limitation of calculation ability and ANSYS software, the printing plate model is simplified and the ink layer is regarded as the uniform flow field. Based on the shortcomings of this paper, the ink transfer mechanism of fluid–solid thermal coupling can be further studied; for example, the compression deformation under dynamic behavior can be considered in the static compression stage. In addition, due to the objective conditions, this paper is based on field printing research and is not an in-depth analysis of more possible printing parameters. It is hoped that researchers in the future can continue to carry out research in this field, expand the sample size, and reveal its nature and mechanism from a theoretical perspective.

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