Study on the Influence of Printhead Intake Velocity on Pressure of Sand Mold 3D Printer

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Abstract. To achieve the precise forming of sand mold for 3D printing, the relationship between the printhead intake and the pressure fluctuation in the printhead during startup and printing of sand mold 3D printer was studied, and the relationship between the two and the causes of pressure fluctuation is analyzed. With the help of computational fluid dynamics and Fluent software, the internal flow model at a single nozzle is established, and the ink flow under 10 groups of different inlet velocities is simulated to obtain the flow contour and pressure fluctuation values. Combined with the small-channel gas-liquid flow pattern, the relationship among the air intake velocity and the pressure fluctuation and the reasons for the pressure fluctuation are analyzed. The results show that with the increase of intake velocities, the pressure fluctuation amplitude increases. In addition, the disturbance degree of gas-liquid interface wave leads to the difference of pressure fluctuation amplitude as the gas-liquid flow pattern changing. The simulation results agree with the experiments. Therefore, according to the relationship between the intake velocity and the pressure fluctuation amplitude, the stability of the printing system can be improved by limiting the speed ratio of supply pump and return pump.

1. Introduction
Sand mold 3D printing technology is a rapid manufacturing technology of non-mold based on droplet injection principle. It adopts the principle of layer-by-layer superposition manufacturing, and has the characteristic of digitization, precision, complexity, flexibility and environment-friendly [1-3]. With the development of sand mold 3D printing technology, higher requirements are put forward for the forming size, precision and efficiency of sand mold 3D printer, which promotes the development of sand mold 3D printer to large-scale. The increase in the number of printheads and in the complexity of ink path make sand mold 3D printer more vulnerable to external interference. The external disturbances in the forming process of sand mold 3D printer mainly include printhead intake, mechanical vibration and electrical signal interference. The above disturbances are easy to cause the fluctuation of printhead pressure of sand mold 3D printer, so that the stability and uniformity of the pressure are not guaranteed, resulting in changes in speed and position of the printhead jet ink droplets, affecting the printing effect.
The printhead intake is the most common disturbance in actual production, and its relationship with the pressure fluctuation in the printhead remains to be explored.

At present, the research of scholars in domestic and international mostly focuses on the influence of various factors on the formation, shape and velocity of ink droplets, focusing on the dynamic analysis of the mechanical structure of the printhead and the influence of the existence of impurities in the printhead on the injection of ink droplets are few studies on the fluctuation of the pressure environment in the printhead [6-8]. Lee[9] found that optimizing the piezoelectric ceramic drive voltage pulse amplitude frequency, ink characteristics and ejection frequency, the shape of the ink-air contact surface, and the ink temperature when ejectionink droplets is beneficial to improve the ejection effect of ink droplets. Wei Dazhong et al. [10] simplified the internal ink flow in the cavity model of the piezoelectric-droplet ejector, and proposed the design method of piezoelectric actuator and cavity structure. Shi Min [11] predicted the volume and velocity of jet ink droplets by using volume of fluid method, and determined the influence of viscosity, density and surface tension of ink droplets on droplet formation. Wijshoff [12] studied the offset effect of trapped bubbles in the printhead on the pressure wave transmission, but the influence of gas flow in the printhead on printhead pressure environment and the relationship between intake velocity and pressure fluctuation were not further studied. In terms of gas-liquid two-phase flow, Kandlikar et al. [13] proposed the standard for dividing small channels according to hydraulic diameter. For the flow pattern of gas-liquid two-phase flow in small channels, researchers also give their own classification criteria according to their research conditions [14]. Since the internal structure of the printhead is complex and small, and the internal flow is not easy to observe, computation fluid mechanics is an ideal tool for analyzing the fluid flow in the printhead [15]. Combined with the structure and working mode of the current sand mold 3D printer, the numerical simulation method is used to analyze the internal flow pattern of the printhead, and the pressure fluctuation under different intake velocity is obtained. Then the relationship between intake velocity and pressure fluctuation and the causes of pressure fluctuation are analyzed, and measures are taken to improve the stability of the system.

2. Three-dimensional Numerical Simulation Model of Fluid in Printhead

2.1. Simplified Fluid Model

Fig.1 shows the schematic diagram of the printhead structure of sand mold 3D printer, which is mainly composed of the printhead inlet, outlet, nozzle, piezoelectric ceramic (PZT) and inner flow channel composition. Ink flow from the printhead inlet to the printhead outlet and circulates above the nozzle. When the piezoelectric ceramic component receives the electrical signal, the piezoelectric ceramic deforms to produce a pressure wave, and the squeezed ink is sprayed from the nozzle to form ink droplets. When ink droplets are needed, the piezoelectric ceramic components remain static. The internal pressure of the printhead is adjusted by the ink supply system. Fig.2 shows the structure diagram of the ink supply system. The pressure adjustment is completed by adjusting the flow rate of the supply pump and the return pump.
According to the structure and actual size of printhead, the internal fluid of the printhead is simplified and the three-dimensional model is established. Fig.3 shows the simplified model. Table 1 shows the geometric parameters of the model.

| Geometric parameters of the model |   |
|----------------------------------|---|
| Model length/mm                 | 9.00 |
| Model width/mm                  | 0.10 |
| Model height/mm                 | 2.10 |
| Nozzle diameters/mm             | 0.07 |
| Area of inlet and outlet/mm²    | 0.08 |

The ink is made of furan resin binder for sand mold 3D printing. The density is 1000 kg/m³, the viscosity is $1.003 \times 10^{-3}$ Pa·s, and the air density is 1.225 kg/m³, and the viscosity is $1.789 \times 10^{-3}$ Pa·s. The physical model of fluid in printhead is assumed as follows:

1. The medium is incompressible Newtonian fluid;
2. The fluid viscosity and specific heat at constant pressure in the printhead are constant, and adiabatic isentropic flow is performed in the printhead;
3. Ignoring the effect of temperature on flow process;
4. The wall is stationary without slip boundary.
2.2. Mesh Generation
Hexcore is used to mesh the simplified physical model, and 1478705 grid nodes and 329642 grids are generated. Fig.4 shows the overall meshing results of the fluid in the printhead. Since the nozzle is the main part of intake, gas-liquid mixing will occur near the nozzle, and the calculation is complex. In order to ensure the accurate calculation results and calculation efficiency, the grid at the nozzle is refined, and the division results are shown in Fig.5.

2.3. Calculation Model
The printhead air intake is a process in which external air enters the printhead from the nozzle under the disturbance of the sand mold 3D printer, and flows with the ink flow inside the printhead. This process is a gas-liquid two-phase flow process. According to the actual flow situation, a standard κ-ε model with small calculation amount, good calculation accuracy and convergence is selected for calculation. There are three Euler multiphase flow models in computational fluid dynamics. Among them, the VOF model is a surface traction method that tracks the volume fraction of each phase member in all calculation units. It has the advantages of easy implementation, small calculation amount and high accuracy [16]. Therefore, this paper uses the VOF method to track the gas-liquid interface. In the VOF model, the interface between the phases is tracked by solving the continuous equation of the volume fraction of one or more phases. In the unit, if the volume ratio of the phase $q$ medium is $\alpha_q$, then $\alpha_q=0$, which means that the phase $q$ medium is empty in the unit; $\alpha_q=1$, which means that the phase $q$ medium is full in the unit; $0<\alpha_q<1$, which means that the unit contains the interface between the phase $q$ medium and the other one-phase or multi-phase medium. The governing equation is as follows:

$$\frac{\partial \alpha_q}{\partial t} + \vec{v} \cdot \nabla \alpha_q = 0$$

In the formula: $\alpha_q$ is the volume fraction of the phase $q$, $\vec{v}$ is the flow velocity of the medium.

2.4. Boundary conditions
According to the ink flow in the printhead and the air content at the outlet in actual work, the boundary conditions of the simulation model are set. The printhead inlet is supplied with ink by the pump, and the air enters the printhead from the nozzle. The air intake velocity of the nozzle is different according to the degree of disturbance. Set the printhead inlet as the velocity inlet, and the velocity is 0.037 m/s. The nozzle is also set as the velocity inlet, and 10 groups of different intake velocity values are given. Set
the outlet as the pressure outlet, take a fixed value of -15 Pa, to facilitate the observation of the pressure fluctuation range at the inlet and the nozzle, and use a non-slip solid wall. Table 2 shows the specific boundary condition value settings.

**Table 2. Model parameter settings**

| Simulation number | Velocity of inlet/m·s\(^{-1}\) | Pressure of outlet /Pa | Velocity of nozzle /m·s\(^{-1}\) |
|-------------------|---------------------------------|----------------------|----------------------------------|
| 1                 | 0.037                           | -15                  | 0                                |
| 2                 | 0.037                           | -15                  | 0.064                            |
| 3                 | 0.037                           | -15                  | 0.128                            |
| 4                 | 0.037                           | -15                  | 0.192                            |
| 5                 | 0.037                           | -15                  | 0.256                            |
| 6                 | 0.037                           | -15                  | 0.320                            |
| 7                 | 0.037                           | -15                  | 0.384                            |
| 8                 | 0.037                           | -15                  | 0.448                            |
| 9                 | 0.037                           | -15                  | 0.512                            |
| 10                | 0.037                           | -15                  | 0.576                            |

3. Calculation Results and Analysis

The solver is defined as pressure solver, and the unsteady solution is selected, and the velocity coupling adopts the widely used SIMPLE flow field solving algorithm. Initially, the printhead inlet and nozzle set the gas phase volume fraction to 1, and perform 200 iterations of calculation. After the initial calculation is completed, the volume fraction of the inlet gas phase is set to 0, and the ink begins to enter the printhead from the inlet. After iterative calculation, the pressure changes at different intake velocity are read respectively. Fig.6 shows the real-time change curves of inlet pressure \(p_1\) and meniscus pressure \(p_2\) when the intake speed is 0 and 0.576 m/s. It can be seen from the pressure change curve that when the air intake velocity is 0, the printhead will not produce pressure fluctuations after being filled with ink. When the air intake velocity is 0.576 m/s, the printhead interior is in a gas-liquid two-phase flow process, and there is a large pressure fluctuation at the inlet and meniscus of the printhead.

![Fig. 6 Pressure curve of inlet and meniscus](image-url)
As shown in Fig. 7, according to the pressure fluctuation amplitude value obtained by the simulation result, draw the pressure fluctuation amplitude curve of the meniscus and the inlet at different intake velocity. It can be seen from Fig.7 that the greater the air intake velocity, the greater printhead pressure fluctuation. When the intake velocity is below 0.2 m/s, the pressure fluctuation changes gently. When the intake velocity reaches 0.2 m/s, the change trend of pressure fluctuation amplitude in printhead becomes larger, and the pressure fluctuation value is about 10 Pa. In the actual work of the sand mold 3D printer, the pressure deviation of the printhead cannot exceed the set value of 200 Pa, otherwise there will be line shortage or ink leakage, and can’t print normally. When the pressure fluctuation amplitude is 10 Pa, it is in the pressure adjustment range, but it has little effect on the print quality and can be ignored. When the pressure fluctuation amplitude reaches 50 Pa, it is 25% of the maximum deviation of the specified pressure. The printing process is prone to uneven ink jetting, which affects the quality of the printed parts.

Fig. 7 Curve of pressure fluctuation amplitude of meniscus and inlet

Fig. 8 shows the ink volume fraction contour when the nozzle air velocity is 0.128 m/s, 0.256 m/s, 0.384 m/s, 0.512 m/s. It can be seen from the image that as the air intake velocity increases, the gas content in the printhead becomes larger, and the flow pattern of the gas-liquid two-phase flow in the printhead changes. As shown in Fig. 9, Oshinowo et al. [17] proposed the principle of flow pattern division. It can be seen that the flow pattern in the printhead undergoes changes similar to bubble flow, plug flow and wavy flow with the increase of air intake velocity, and the disturbance of the gas-liquid interface wave becomes more and more severe, resulting in increase in the amplitude of the pressure fluctuation. It is consistent with the change trend of the curve shown in Fig.7, and also consistent with the variation trend of pressure difference fluctuation under different flow patterns.
Therefore, for the printhead air intake phenomenon, the faster the air intake velocity, the more and more severe the disturbance of the gas-liquid interface wave, which causes the pressure fluctuation amplitude in the printhead to become larger and larger, and it takes longer for the sand mold 3D printer to calm the pressure fluctuation. When the air intake velocity is less than 0.2 m/s, the flow in the printhead is in a state similar to bubble flow. Because the energy of small bubbles is very small, the pressure fluctuations generated when the bubbles are generated and collapsed are also small, which has little impact on the system. According to the structure of the ink supply system shown in Fig.2, the main factor that affects the air intake velocity of the printhead is the pump speed difference between the supply pump and the return pump. Therefore, the supply pump and the return pump can be restricted in the control program. The pump speed ratio of the pump reaches the limit of the air intake velocity, and the flow state in the printhead is stabilized in bubble flow or single-phase liquid flow, and the stability of printing is improved.

4. Experimental Verification
Fig.10 shows the experiment device, which consists of ink tank, supply pump, return pump, filter, damper, piezoelectric printhead, and pressure sensor detection system. Both the supply pump and the return pump use KNF’s NFB60 diaphragm pump, the pressure sensor is XGZP6874A, the range is -1~1 kPa, the filter is a large PALL 5UM barrel filter, and the printhead is Xaar 1002. Since the pressure at the nozzle of printhead is difficult to measure in actual operation, the fluctuation amplitude of the pressure difference between the inlet and outlet of the printhead is measured here and the simulation result is compared. Another characterization of the air intake velocity in the simulation is the volume fraction of the air in the printhead in total medium. Therefore, the air intake velocity of the printhead is controlled by controlling the flow of the supply pump and the return pump, and then by collecting the
feedback signal of the pressure sensor, the change of the fluctuation amplitude of the inlet and outlet pressure difference is obtained.

Fig. 10 Schematic diagram of experiment device

The pump output flow rate is determined by the control voltage and is in direct proportion. The relationship between the pump flow rate and the control voltage measured by the test is:

\[ Q = 264.01U - 214.42 \]  \( (2) \)

In the formula: \( Q \)—pump output flow, mL/min. \( U \)—control voltage, V.

Set the driving voltage of the supply pump to be constant at 1.5 V, and the ink flow rate is about 181.595 mL/min. From equation 2, the corresponding relationship between the printhead air intake and the driving voltage of the return pump can be obtained. Table 3 shows the corresponding relationship between the driving voltage of the return pump and the air content, and the experiment is carried out according to Table 3.

Table 3. Correspondence between the driving voltage of the return pump and the air content of printhead

| Drive voltage/V | 1.5  | 1.6  | 1.7  | 1.8  | 1.9  | 2.0  |
|-----------------|------|------|------|------|------|------|
| Air content/%   | 0    | 12.7 | 22.5 | 30.4 | 36.8 | 42.1 |

The relationship curve between the amplitude of the inlet and outlet pressure difference fluctuations and the air content \( N \) measured in the experiment is shown as the solid line in Fig.11. The relationship between the inlet pressure fluctuation amplitude and the intake velocity in Fig.7 is transformed into the relationship with the air content. As shown in Fig.11, the two curves are presented in the same figure and compared.

Fig. 11 Pressure Fluctuation amplitude curve of experiment and simulation
It can be seen from Fig.11 that the measured curve also has pressure fluctuation when the gas content is 0. Since the adopted pump is diaphragm pump and intermittent ink supply, even if the damper is used to attenuate the flow pulsation, the flow pulsation cannot be completely eliminated. Therefore, the pressure fluctuation when the gas content is 0 may be caused by the flow pulsation. When the gas content is low, the pressure fluctuation is small, and the difference between the experimental value and the simulation value is small, with the error within 20%. When the gas content gradually increases, the pressure fluctuation value increases, and the experimental value begins to have a large deviation from the simulation. At this time, the maximum error can reach about 37%. Since the pipeline used in the experimental device is a hose, the pump will produce a certain vibration when it works, and the ink pipe is affected to some extent. The larger the pump flow, the more severe the vibration, and the influence of temperature changes in the tube is not considered in the simulation, which may be the cause of the larger error. From the overall comparison between the experiment curve and the simulation curve, it can be seen that the change trend of the two is roughly the same. The simulation result is considered correct when the error of the pressure sensor, the flow pulsation of the pump and other interference are ignored.

5. Conclusion
Based on the structural characteristics of the sand mold 3D printing printhead, the influence of printhead air intake on the pressure inside the printhead was analyzed by numerical simulation, and the printhead ink supply experiment device was built to verify the numerical simulation results. According to the results of numerical analysis, it is found that the greater the printhead intake velocity, the greater the amplitude of pressure fluctuations in the printhead. When the intake velocity is above 0.2 m/s, the change trend of pressure fluctuation amplitude increases. The flow pattern of gas-liquid two-phase flow in the printhead changes of bubble flow, plug flow and wavy flow with the increase of intake velocity. The transition point of bubble flow and plug flow is near the intake velocity of 0.2 m/s, which is close to the position of the change point of the increasing trend of the pressure fluctuation amplitude in the printhead. Therefore, the reason for the increasing trend of the pressure fluctuation amplitude in the printhead may be the change of the flow pattern. When the intake velocity is less than 0.2 m/s, the pressure fluctuation amplitude is within 10 Pa, which has little effect on the printing process. Therefore, in the process of pressure regulation of the ink supply system, the pump speed ratio of the supply pump and the return pump can be added to limit the intake velocity of the printhead and improve the stability of the system. Compared with the numerical simulation results, the variation trend of pressure fluctuation amplitude is consistent, so the numerical simulation results are reasonable.

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