

Analysis of fluid dispensing performance of automated dispensing machines based on finite element method

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Abstract: An Automatic dispensing machine is an automated equipment that realizes glue positioning, quantification, and timed coating through a high-precision control system. Compared with traditional dispensers, its core feature lies in the precise control of glue output and motion trajectory, which is suitable for small glue dots and complex path operation needs, such as precision instrument assembly, LED chip dispensing, and other scenarios. In order to better optimize the performance of the automatic dispensing system and improve the accuracy and stability of dispensing, finite element analysis theory is used to simulate the physical phenomena, such as glue flow and pressure distribution, in the dispensing process. The influence of the needle inner diameter is more sensitive when the inner diameter is smaller. Longer needles significantly reduce dispensing efficiency due to increased flow resistance.

1. Introduction

Dispensing machines play a pivotal role in industries such as electronics manufacturing and precision instrument assembly. Their primary function is to deposit glue or other adhesives onto precise positions of components to facilitate processes like bonding, fixing, and sealing. Such machines are integral to electronic assembly, precision instrument manufacturing, and automobile parts production. Historically, traditional dispensing machines relied heavily on manual operation, which resulted in low work efficiency and a high susceptibility to errors. This limitation has spurred continuous technological advancements, leading to the ongoing upgrading and development of dispensing machinery. The automatic and continuous application of glue to the aluminum base of LED waterproof strip lights was achieved by a specially designed dispensing machine^[1]. An optimization was performed on the technical parameters of a fully automatic five-axis round hole dispensing machine^[2]. A PLC-based control system was designed for an automatic dispensing device^[3]. To address issues such as small displacement and low dispensing accuracy in traditional micro-dispensing mechanisms, a compact micro-dispensing mechanism driven by piezoelectric ceramics^[4]. A peristaltic pump was used as the dispensing device of a dispensing machine, and a four-axis dispensing control system was designed to precisely control the dispensing process^[5]. Structural design and optimization were performed on the dispensing module of RFID tag packaging

equipment^[6]. An automatic precision dispensing system is proposed and designed to realize the accurate control of the dispensing process and to be integrated into the micro assembly equipment^[7]. To achieve uniform glue dispensing and a dispensing direction perpendicular to the curved surface in mobile phone frame processing, a dual B-spline interpolation algorithm based on a five-axis glue dispensing machine was investigated^[8].

Automatic dispensing machines utilize automated control and high-precision dispensing technology to accomplish large-scale adhesive application in a short time, thereby enhancing production efficiency. Representing the integration of intelligent manufacturing technology into the dispensing sector, these machines offer substantial support for the ongoing intelligent transformation of the manufacturing industry.

2. Design of the Automatic Dispensing Machine

2.1. Structural Design of the Dispensing Machine

The automatic dispensing machine designed in this project is intended for a mixed integrated circuit production line. The dispensing machine uses a stepper motor for guidance and achieves motion control through forward movement driven by a gear and rack, as shown in Figure 1.

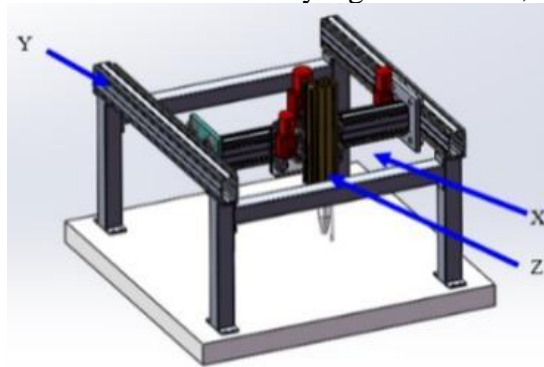


Figure 1. Mechanical Structure Diagram of the Automatic Dispensing Machine.

The dispensing machine moves along the X, Y, and Z directions, driven by stepper motors that actuate the gears. The motion is controlled through a PLC program. With the cooperation of the gears and racks, the dispensing head is moved from different positions to specified locations by the gears, and then performs the designated operation via the dispensing head.

2.2. Design of the Dispensing Control Process

In this project, the dispensing control process is implemented by adjusting the air source through a pressure proportional adjustment valve and storing it in an air pressure stabilizer. The high-pressure gas is then delivered to the container through a pipeline connected to the pressure stabilizer, as shown in Figure 2.

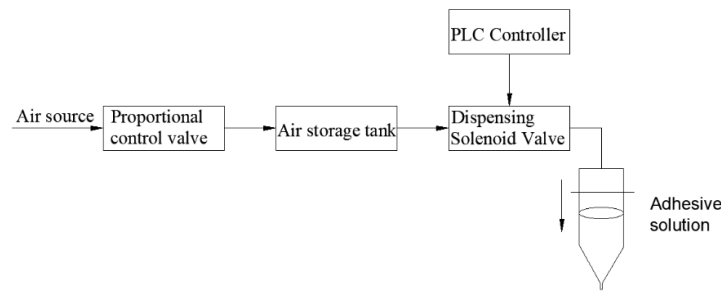


Figure 2. Schematic diagram of the dispensing control system.

The solenoid valve controls the air tube switch. When the solenoid valve is open, it pushes high-pressure gas into the test tube, causing the liquid inside the tube to flow out. When the solenoid valve is closed, the test tube is cut off from the gas, and the viscous liquid inside the test tube stops flowing. The volume of colloid discharged from the needle is adjusted by the air pressure of the gas source (i.e., the dispensing pressure) and the open/close time of the solenoid valve (i.e., the dispensing time). High pressure for a long time in the test tube produces more gel. In addition, to prevent slow discharge of the glue due to gravity during the work process, a certain vacuum pressure is required for its absorption. Essentially, this control method uses the combined effect of time and pressure to control the size of the colloid outflow.

3. Analysis of Dispensing Performance of Automatic Dispensing Systems

During the operation of a dispensing machine, analyzing fluid properties is crucial. It directly affects the quality, precision, and efficiency of the dispensing process. The viscosity of the adhesive is a key factor. High-viscosity adhesives face greater resistance during flow, require higher pressure to be dispensed from the needle tip, and are prone to stringing. On the other hand, low-viscosity adhesives flow more easily but may struggle to maintain shape and stability in certain situations.

The flow behavior of adhesives is a core physical property of their dispensing process. The vast majority of industrial adhesives, such as epoxy resins, silicones, and UV-curable adhesives, exhibit complex non-Newtonian fluid characteristics, with viscosities that are not constant but highly dependent on shear rate, time, and even temperature. Treating adhesives simply as Newtonian fluids can lead to simulation results that deviate significantly from reality.

To accurately analyze the fluid performance of the dispensing machine, this project establishes a mathematical model to simulate and predict the flow of adhesive in complex structures. By conducting an in-depth analysis of these fluid performance parameters, the study enables optimization of the dispensing machine's working parameters—such as dispensing pressure, needle size, and movement speed—achieving more precise and efficient dispensing operations.

3.1. Finite Element Modeling of Colloids

This project plans to use ANSYS 14.0 software for modeling and analysis. According to practical requirements, the project selects the 18G microprocessor produced by a company in Shenzhen as the research object. Table 1 lists the product specifications. The adhesive used is 3M-2216 high-elastic structural adhesive, and the colloid and related parameters are shown in Table 2, with data sourced from the same industry.

Table 1. Needle Specifications.

Model	Inner Diameter (mm)	Outer Diameter (mm)	Length of Needle Tube (mm)
18G	0.84	1.26	25

Table 2. Technical parameters of the glue and dispensing.

Colloidal Viscosity (CPS)	Density of Colloid (kg m^{-3})	Air Pressure in The Test Tube (MPa)	Atmospheric Pressure (MPa)	Colloid Height (mm)	Syringe Inner Diameter (mm)
80000	1250	0.24	0.1	40	24

Before performing finite element analysis, the model needs to undergo preprocessing. First, the computational domain is divided, and the physical properties within the domain (including the model, material properties, boundary conditions, and algorithm control) are described in detail as follows:

(1) The colloid is assumed to follow a fully developed steady laminar flow pattern, and the pressure inside the lumen is assumed to be constant throughout each dispensing cycle. In this case, during a single dispensing cycle, the dispensing pressure rapidly reaches and maintains stability. The dispensing cycle is longer than the adjustment time required for the air pressure in the syringe to rise. Once the pressure reaches a certain level, the dispensing volume is determined by the dispensing process.

(2) The material properties are adjusted according to the relevant parameters of the colloid characteristics in Table 2, especially the fluid property parameters for density and viscosity.

(3) Boundary conditions are set, applying the No-Slip condition at boundary contact points, with the static air pressure at the inlet set at 0.24 MPa and the static air pressure at the outlet set at 0.1 MPa.

3.2. Rheological Properties of the Colloid

The colloid model was sheared using CFX-Post software, resulting in the velocity contour of the colloid flow in the model shown in Figure 3. The darker the color, the faster the flow velocity.

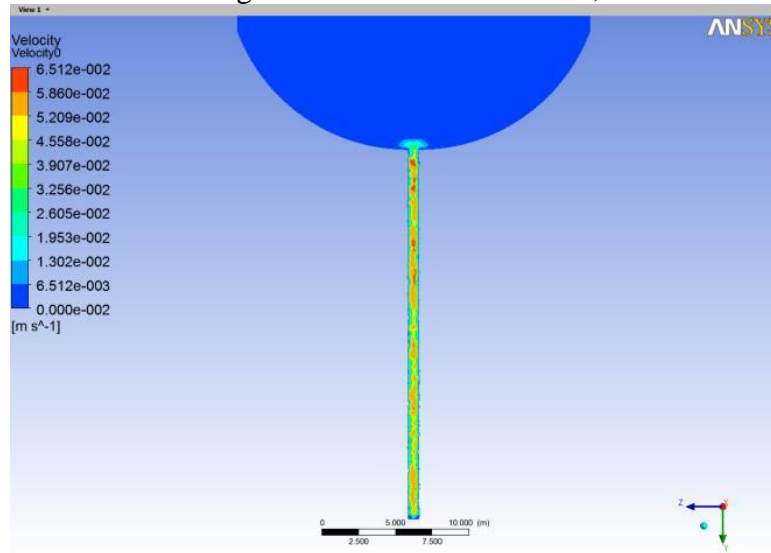


Figure 3. Flow Velocity Distribution Diagram.

By analyzing Figure 3, the following conclusions can be drawn:

(1) In the syringe, the flow velocity of the colloid is very small, approximating zero, which indicates that when constructing the syringe model, it is correct to neglect the flow velocity within the syringe.

(2) At the location of the injection needle, the velocity of the liquid adhering near the needle wall is minimal, close to zero, and the velocity of the colloid flow increases from the wall towards the center, which is consistent with the characteristics of laminar flow.

(3) At the junction between the injection needle and the syringe tube, the complexity of its shape causes the distribution of flow velocity to be relatively disordered.

(4) From the flow distribution shown in the figure, it can be seen that the colloid flow varies significantly in the Z-direction (axial direction), with a greater rate of change occurring closer to the needle wall. This result supports the previously proposed hypothesis that "colloidal particles only move axially within the syringe."

A streamlined distribution diagram of the dispensing model is shown in Figure 4. From the figure, it can be seen that at a specific moment, different fluid particles are distinctly distributed in the flow field. The direction of the velocity vectors of fluid particles coincides with the tangent direction; the denser the streamlines, the faster the velocity, and the sparser the streamlines, the slower the velocity. Observations show that in the needle, the density of streamlines is much greater than in the syringe, indicating that the flow rate of the glue in the needle is much higher than in the syringe, and the colloid primarily flows along the injection axis during the injection process.

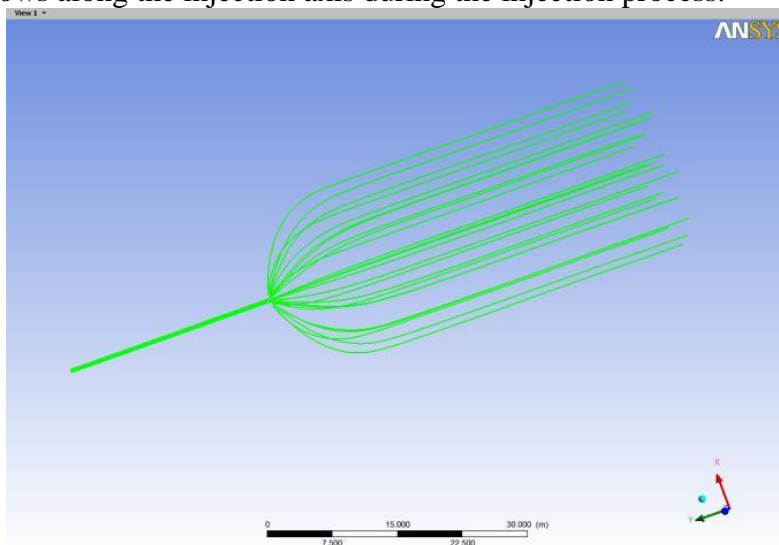


Figure 4. Distribution of Spatial Streamlines.

The distribution of streamline velocity in the Z direction is shown in Figure 5. It can be seen that the flow velocity of the colloid gradually increases from the needle wall to the center, and the flow velocity is highest along the needle axis.

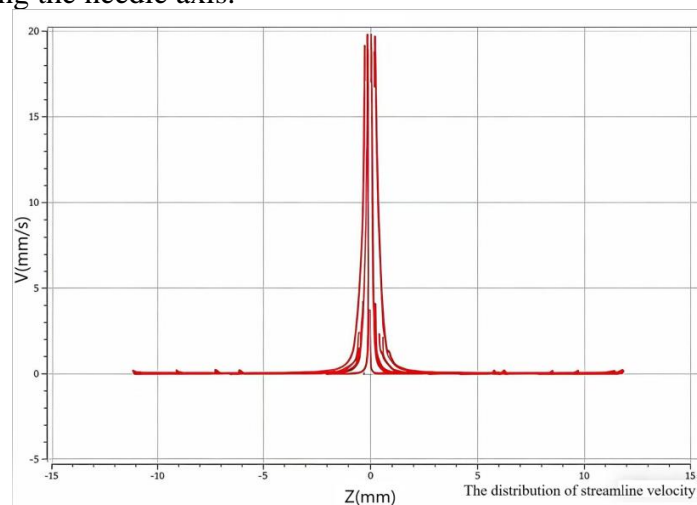


Figure 5. Streamline velocity distribution diagram.

3.3. Effect of Inlet Pressure on Gel Output

Using the method of controlling variables, the relationship between inlet pressure and gel output was analyzed. By changing the inlet pressure while keeping the colloid characteristics, needle characteristics, and outlet pressure constant, the average flow rate at the outlet pressure was obtained. The outlet speed was used to describe the gel extrusion rate. The data results were fitted using Origin software, resulting in Figure 6.

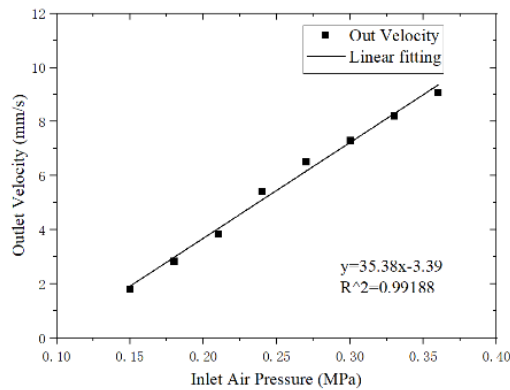


Figure 6. Fitting of Inlet Air Pressure and Outlet Velocity.

Based on the line graph in the figure, the following conclusions can be drawn:

(1) Near the outlet, there is a significant linear positive correlation between the colloid outlet velocity V_t and the air inlet pressure P_0 . As the inlet pressure increases, it provides greater driving potential for the colloid flow, resulting in a linear increase in the colloid extrusion rate.

(2) Near the outlet, the colloid outlet velocity V_t shows an approximately linear relationship with the air inlet pressure P_0 . Each time the inlet pressure P_0 increases, the colloid velocity V_t increases by approximately 3.538 mm/s, which roughly satisfies the following relationship:

$$V_t = 35.38P_0 - 3.39$$

3.4. Effect of Needle Inner Diameter on Dispensing Volume

Using a controlled variable method and keeping the colloid properties, needle length, and inlet and outlet pressures constant, the study varied the needle inner diameter. The average velocity at the needle outlet was measured, and the dispensing volume was characterized by the outlet velocity. The data results were fitted using Origin software, resulting in Figure 7.

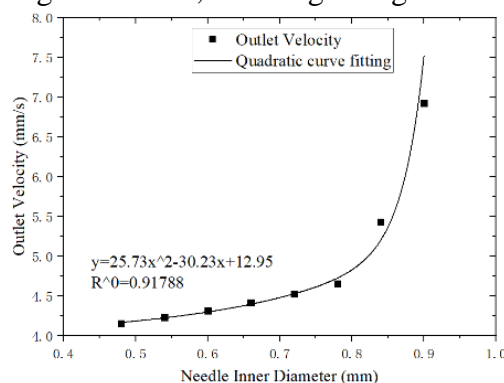


Figure 7. Fitting of colloid extrusion speed and needle diameter.

Based on the line graph in the figure, the following conclusions can be drawn:

(1) Near the outlet, there is a significant nonlinear positive correlation between the colloid extrusion speed and the needle diameter. As the inner diameter increases, the flow resistance decreases significantly, resulting in an increased extrusion rate.

(2) There is a critical point in the trend of flow rate increase (approximately $d_i \approx 0.8$ mm).

When $d_i < 0.8$ mm, the flow channel is narrow, and flow resistance is dominant and varies significantly. A slight increase in the inner diameter has a very noticeable effect on reducing resistance and increasing flow velocity.

When $d_i > 0.8$ mm, the flow channel is relatively spacious and resistance is relatively low, so further increases in the inner diameter gradually have a diminishing effect on improving flow velocity (the slope of the curve decreases).

(3) When the needle diameter is 0.4-0.9 mm, the relationship curve between the colloid outlet velocity V_t at the outlet and the needle inner diameter d_i is approximately. A quadratic parabola roughly follows the following relationship:

$$V_t = 25.73d_i^2 - 30.23d_i + 12.95$$

3.5. Effect of Needle Length on Dispensing Volume

On this basis, using a controlled variable method, the study examined the effect of needle length on the dispensing rate. By changing the needle length, needle inner diameter, inlet pressure, and colloid characteristics, the dispensing speed was determined and represented by the outlet velocity. Without changing the colloid properties, needle diameter, inlet pressure, or outlet pressure, the outlet colloid flow velocity was obtained by varying the needle length.

The data results were fitted using Origin software, resulting in Figure 8.

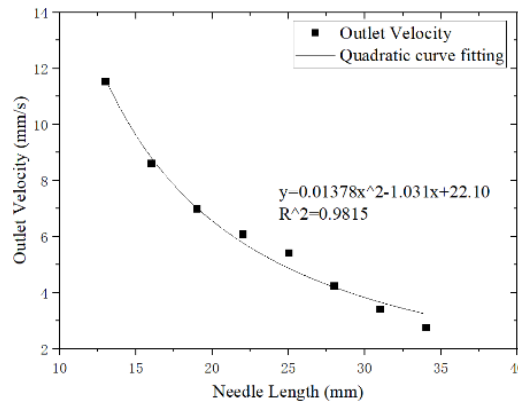


Figure 8. Fitting of the Relationship between Needle Length and Outlet Velocity.

According to the broken line in the figure, the following conclusions can be drawn:

(1) At the outlet position, the colloid outlet flow velocity V_t is significantly nonlinearly negatively correlated with the needle length l . As the needle length increases, the resistance along the flow path of the colloid increases, consuming more driving pressure, which leads to a decrease in the extrusion rate.

(2) The extent of the velocity decrease is not uniform: the longer the needle (e.g., in the 34 mm to 25 mm range in the figure), the more pronounced the suppressive effect of increased resistance on the flow velocity (the curve is steeper). For shorter needles (e.g., in the 16 mm to 13 mm range), the reduction in resistance from further shortening the needle yields diminishing returns, and the increase in flow velocity tends to level off.

(3) When the needle length is within a certain range of 10-35 mm, the relationship curve between the colloid outlet flow velocity V_t and the needle length l approximates a quadratic parabola and

roughly satisfies the following relationship:

$$V_i = 0.01378l_i^2 - 1.031l_i + 22.10$$

These conclusions provide an important theoretical and experimental basis for accurately controlling the dispensing process of adhesive dispensing equipment.

4. Conclusions

The simulation analysis of an automatic dispensing system based on finite element theory is conducted in this paper. Through simulation studies on the rheological properties of the adhesive, the effects of inlet pressure, needle inner diameter, and needle length on dispensing volume were analyzed. The results indicate:

(1) Inlet pressure is linearly proportional to the dispensing volume and is the most direct and sensitive parameter for controlling the dispensing volume.

(2) Needle inner diameter has a nonlinear positive correlation with dispensing volume, and its effect is more sensitive at smaller diameters.

(3) Needle length has a nonlinear negative correlation with dispensing volume; longer needles significantly reduce dispensing efficiency due to increased flow resistance.

These conclusions can provide a theoretical basis for the design of automatic dispensing machines.

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