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A new flow controller for medical injection

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Abstract

A new type of flow controller for medical injection was developed and evaluated. The flow rate was controlled by simultaneously varying the friction length and depth of the micro-channel such that the relation between the flow rate and the length of the channel becomes more linear. The micro-channel was fabricated using ultra-precision machining technology. A seal made of butyl rubber was used to stop fluid leakage. The butyl rubber was coated with silicone oil to make the controller rotate smoothly. The flow controller was validated by comparing experimental data with theoretical predictions. Good agreement was found between theory and experiment.

Keywords: Flow controller; Friction length; Medical injection; Butyl rubber

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1. Introduction

Various applications require knowledge of the flow volume passing through a duct. For example, the ability to accurately measure the flow volume passing through an injector is of vital importance when injecting a vein with a given amount of medicine. An injection of Ringer's solution is widely used in hospitals, where the flow rate is controlled by trapping the flow by a sliding roller. However, this method does not allow precise control of flow rate because of manual trapping.

In the present study we develop a new type of flow controller capable of accurate flow control. Instead of the slide roller, most controllers used in hospitals to date, have employed the friction length along a long duct for flow control. However, because the flow rate is inversely proportional to the friction length, the flow rate of flows controlled exclusively by the friction length will be highly sensitive to the friction length in the low flow rate region and insensitive to the friction length in the high flow rate region. This problem is resolved in the present study by varying the depth of the duct such that the relation between the flow rate and the length of the duct becomes approximately linear. This design enables accurate flow control. The proposed controller was validated by comparing experimental data with theoretical

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predictions. The micro-duct was fabricated using ultra-precision machining technology. Seals made of butyl rubber were used to stop fluid leakage; the butyl rubber was coated with silicone oil to make the controller rotate smoothly when operated by hand. The flow rate is controlled in a range $5 \leqslant Q \leqslant 250$ ml/h. The target precision level of the new flow controller is that the relative error is less than 10% in the region $50 \leqslant Q \leqslant 100$ ml/h, which is widely used in hospitals. The approach suggested here has the advantage that it does not infringe upon previously published patents.

2. Design concept and fabrication

First, let us consider the case of fully developed flow in a circular pipe of length L and diameter D that has a pressure drop Δp over its length L. The flow rate through the pipe can be expressed as

$$Q = -\frac{\pi D^4 \Delta p}{128 \mu L} \tag{1}$$

where μ is the fluid viscosity [1]. As seen in Eq. (1), the flow rate can be controlled by adjusting two main parameters, L and D. However, Q is much more sensitive to D ($Q \propto D^4$) than to L ($Q \propto 1/L$). Most flow controllers in current use control the flow rate by changing the friction length L, that is, they employ the relation $Q \propto 1/L$. In the present study, however, both D and L are simultaneously adjusted to control the flow rate such that the relation employed is closed to the form $Q \propto L$.

A schematic diagram of the flow control is shown in Fig. 1. A narrow flow channel with a square cross-section is cut into the circular plate B. The channel runs from b to d and passes through c. The friction length L of the channel is denoted by $L = R\theta$, where R is a radius of the arc of the channel and θ is a rotation angle as shown in Fig. 2. The width of the channel w is fixed, but the channel depth changes from a_1 to a_2 along the friction length L. By placing plate A upon plate B, a closed flow channel is made. As shown in Fig. 2, the friction length is the distance along the arc from c to d. Here, the inlet point c is adjusted by rotating plate B with respect to plate A. The span of c is $b \leqslant c \leqslant d$. The outlet point d is connected to g through e and f. The flow rate is controlled by rotating plate B.

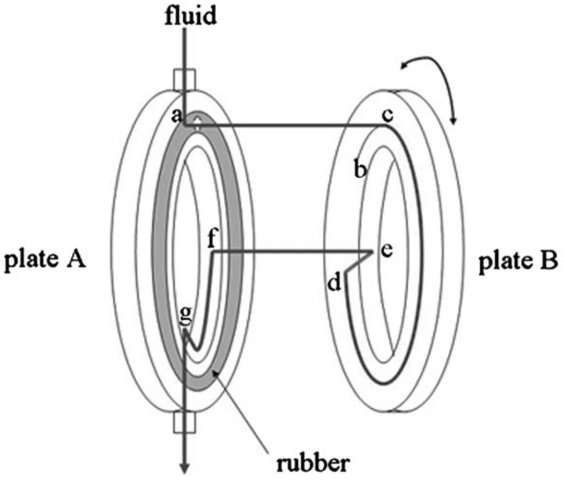

Fig. 1. Schematic diagram of controller.

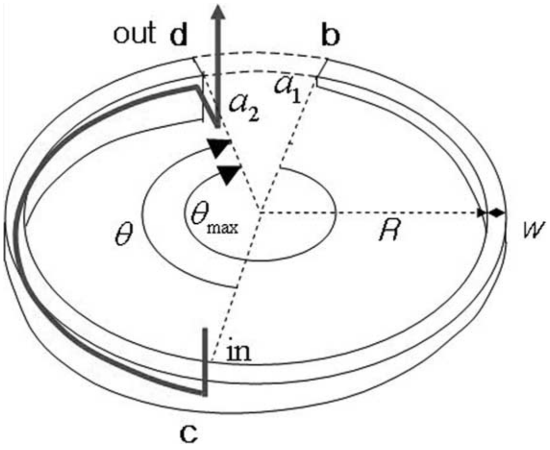

Fig. 2. Friction length ($L = R\theta$) and depth ($D = a_2\theta/\theta_{max}$).

To achieve accurate flow control, the flow channel must be precisely fabricated. The channel was manufactured by using ultra-precision machining technology [2]. This was required because the die structure had very thin channel walls. The error in the dimensions of the fabricated channel was ±10 μm. The manufacturing procedure was developed using the CAD/CAM program. The numerical control data was then directly transferred from the computer to the ultra-precision machine. The ultra-precision machining was performed using carbide-coated endmills with two flutes of diameter 1.0 mm. Optimal machining conditions were obtained at a spindle speed 50,000 rpm and a feed rate 50.0 mm/min [3]. Enlarged views of four points on the fabricated plate A are shown in Fig. 3. The maximum relative fabrication error is less than 3%, which corresponds to a fabrication error of less than 6 μm. Fig. 4 shows the external appearance of plate A. In this figure, the points a through g correspond to those in Fig. 2; the flow enters at point a, passes through points c and d, and then exits through point g. In the present study, the flow rate was controlled in the range $5 \leqslant Q \leqslant 250$ ml/h. The system parameters were as follows; $R = 12.4$ mm, $w = 0.2$ mm, $\theta_{\max} = 17\pi/9$, $a_1 = 0.01$ mm and $a_2 = 0.3$ mm. The pressure drop of the system was $\Delta p = 8000$ Pa. Note that the

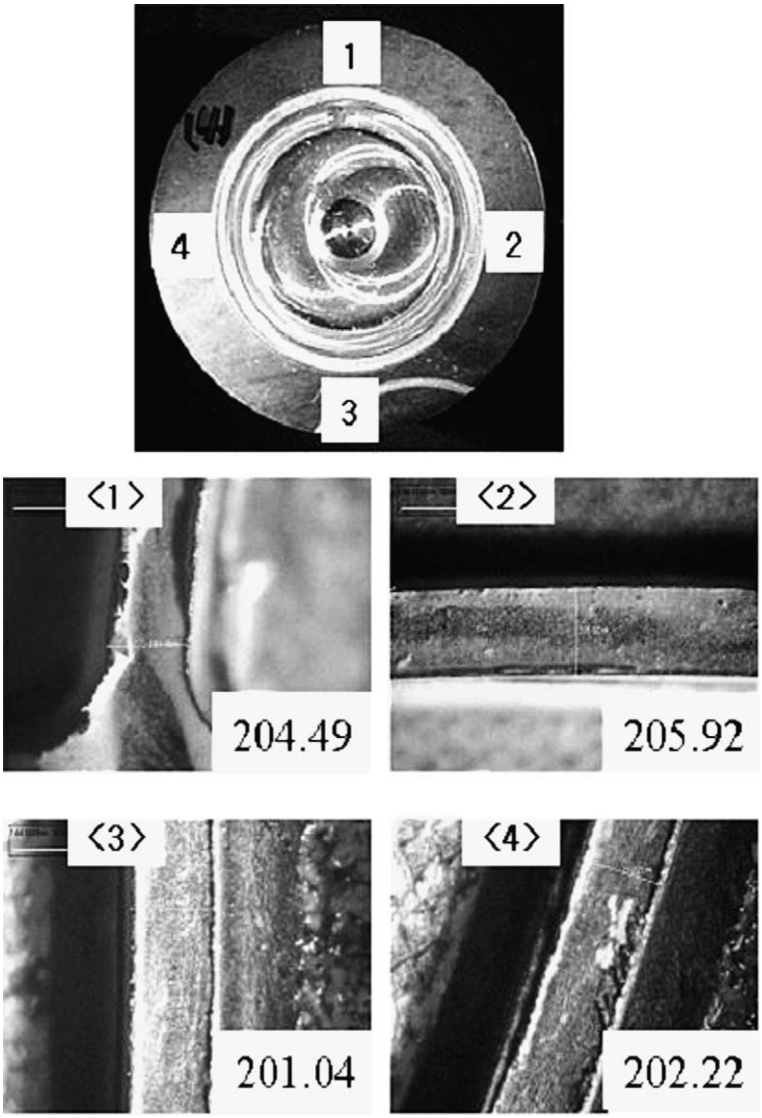

Fig. 3. Enlarged views of fabrication (unit: μm).

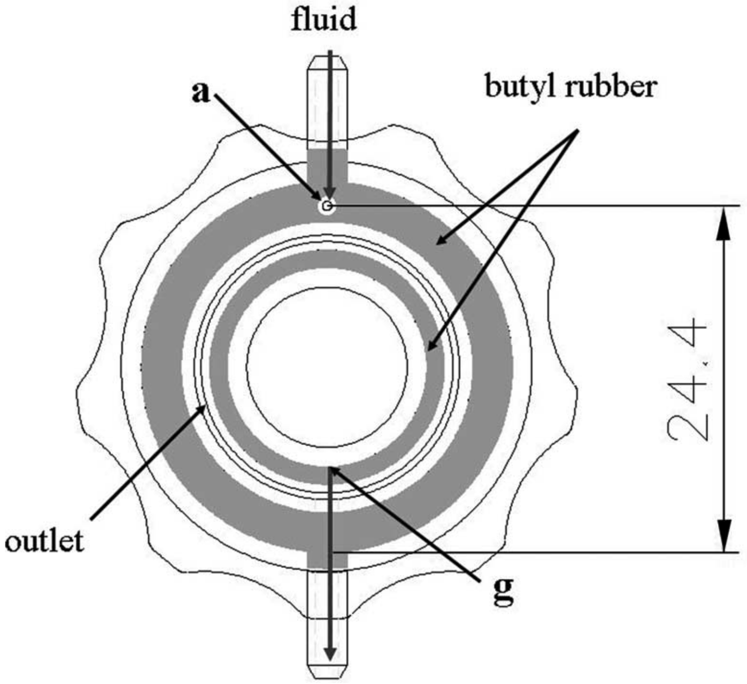

Fig. 4. Plate A (unit: mm).

channel depth a_2 is an important parameter to make a linear relation between Q and L.

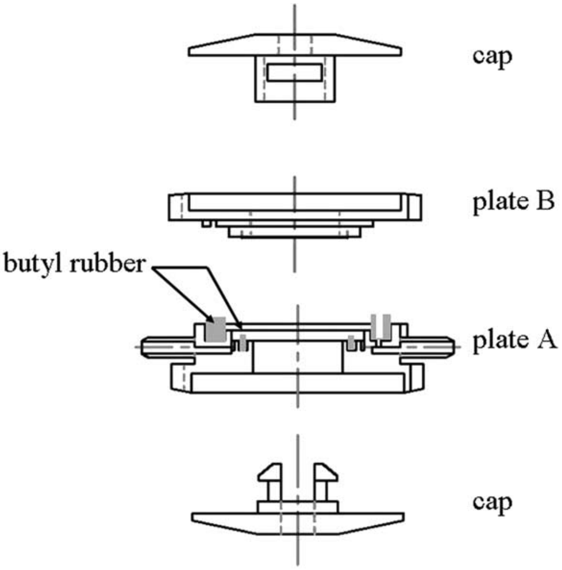

Fig. 5. Assembly of parts.

Care was exercised to prevent flow leakage during flow control. To this end, butyl rubber, a nontoxic material that is softer and more elastic than nitrile butadiene rubber [4], was inserted between the plates as shown in Figs. 4 and 5. Because the flow rate was controlled by rotating the plate by hand, the butyl rubber was coated with silicone oil to provide lubrication [5]. As shown in Fig. 5, the rings of rubber (surplus thickness = 0.29 mm) coated with silicone oil was placed on plate A to adhere closely to plate B. Two polycarbonate caps were joined to combine the plates. The error uncertainty of the caps was within the range ±10 μm.

3. Results and discussion

The reliability and accuracy of the proposed controller was assessed by comparison between theoretical predictions and results obtained from experiments using the fabricated controller. As mentioned above, the flow rate was controlled by simultaneously adjusting the friction length L and depth D. The flow rate measurements were made by counting the number of drops, where the drop was formed from the outlet of the flow controller. The total volume was measured through a mass cylinder with ±0.1 ml uncertainty. The flow rate was calculated by the total volume, the number of drops and the measuring time. As a working fluid, 5% aqueous glucose solution was employed. It was found that the averaged volume of one drop was 0.00994 ml/drop in a range $5 \leqslant Q \leqslant 250$ ml/h, with ±3% maximum error. The pressure drop was $\Delta p = 8000$ Pa.

First, a numerical simulation was performed with constant depth ($D = 2$ mm) and width ($w = 2$ mm) under the assumption of fully developed flow. The pressure drop in Eq. (1) was $\Delta p = 8000$ Pa. As shown in Fig. 6, the flow rate obtained using the fabricated controller with variable channel depth is more liner with respect to the friction length than the flow rate predicted numerically for a channel of constant depth. As expected from Eq. (1), the simulated flow rate with constant depth is very sensitive to the friction length in the region $0 \leqslant L \leqslant 10$ mm, and is very insensitive in the region $L \geqslant 30$ mm. However, by introducing a variable channel depth, the variation in the flow rate with changing friction length becomes more linear because D supports the increase of Q in the high flow rate region but decreases Q in the low flow rate region.

Next, we performed numerical simulations of the controller with variable channel depth, where the simulation parameters were taken to be those of the experimental system. As mentioned earlier, the friction length L is the distance along the arc from c to d. The inlet point c is adjusted by rotating plate B with respect to plate A. The total flow rate can be computed by considering the depth of the channel. As shown in Fig. 7, the experimental and numerical results are in close agreement. The small discrepancy between theory and experiment may be caused by the fabrication error and experimental uncertainty. In the low flow rate region ($Q \leqslant 25$ ml/h), the computed flow rate is more sensitive to the friction length than the experimentally measured flow rate.

Finally, the relative error of the flow controller, defined as the standard deviation relative to mean flow rate at a fixed flow rate of the controller, is shown in Fig. 8 as a function of flow rate. The relative error lies within the range of 8–12% for flow rates in the range $25 \leqslant Q \leqslant 150$ ml/h. Importantly, the relative error is less than 10% in the range $50 \leqslant Q \leqslant 100$ ml/h, which is widely used in hospitals. In the low flow rate region $25 \leqslant Q \leqslant 150$ ml/h, the relative error is very high, probably due to the very small depth in this region. However, the absolute error is negligible at the low flow rate region.

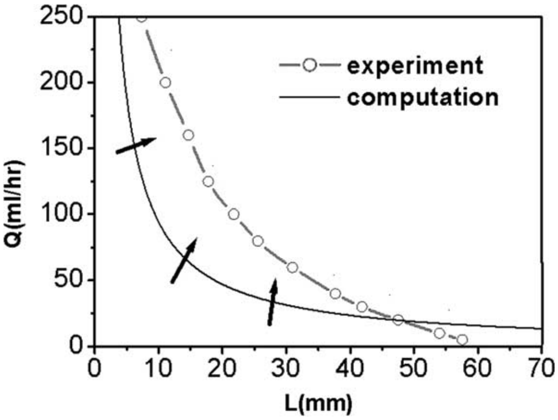

Fig. 6. Comparison between experiment and computation. The computation was made with constant depth ($D = 0.2$ mm).

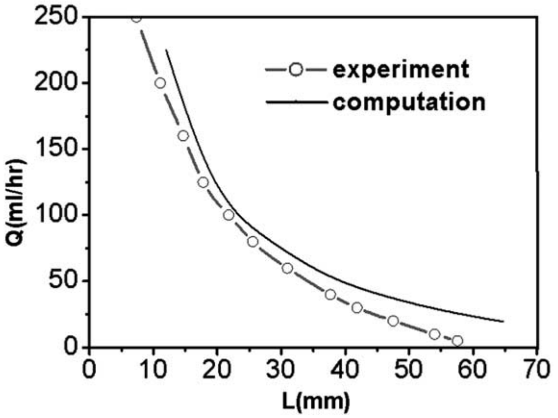

Fig. 7. Comparison between experiment and computation. The computation was made with varying depth.

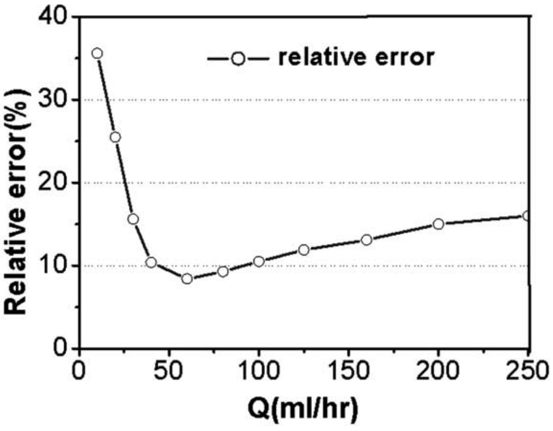

Fig. 8. Relative errors.

4. Conclusions

A new flow controller was developed in which the flow rate was controlled by simultaneously varying the friction length and depth of the micro-channel. The micro-duct was fabricated using ultra-precision machining technology, and the controller was validated by comparing experimental data with theoretical predictions. By introducing a variable channel depth, the variation in the flow rate with changing friction length becomes more linear because the depth supports the increase of the flow rate in the high flow rate region but decreases the flow rate in the low flow rate region.

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