ABSTRACT
Model-based simulation platform for integrated micro-fluid circuit was newly developed to calculate the complicated internal flow precisely and to optimize circuit configuration efficiently. It enables us to form simulation model easily and quickly through connecting blocks corresponding to fluid elements, and deals with transient, unsteady flow. The simulation platform predicts well static characteristics and dynamic response in micro-channel, and is now utilized to design new device - paper MEMS chip.

KEYWORDS: Model-based, Micro-fluid circuit, Simulation, Capillary

INTRODUCTION
Since many sorts of micro-fluid device corresponding to various unit-operation have been available in these years, we are able to deal with complicated chemical processes by connecting those devices in series and by arraying them in parallel[1][2]. However, in the micro-fluid circuit connected with them, their internal flow tends to be unstable due to the unbalance of pressure resistance among them. In addition, the flow-rate varies with the expansion and shrinkage of air bubble and the deformation of elastic, soft material such as plastics, PDMS and paper!. Therefore, practical simulation tools, which allow us to configure simulation-model rapidly by connecting blocks corresponding to fluid-elements such as micro-channels, bifurcation and merging connectors etc., have been desired in order to predict fluid behavior and to optimize system design (figure 1)[3].

MODEL-BASED SIMULATION PLATFORM
Model-based technique, which has been used mainly in motion system, enables us to form the model and simulate them quickly. We applied this model-based simulation technique to the micro-fluid circuit. Since the motion system is normally expressed as lumped mass system, existing mathematical blocks based on the ordinary differential equation are available. On the other hand, since the micro-fluid circuit is expressed as continuous system which allow us to simulate propagation of pressure wave and kinetic momentum, new original blocks based on partial differential equation need to be developed. As shown in figure 2, basic element blocks and complex blocks dedicated to micro-fluid elements were newly created. They are based on the Euler's equation of motion which is used for water hammer analysis, supposing that the inner diameter of micro-channels is much smaller than the channel length and the inner flow is laminar flow. The element blocks are made up with the linkage of finite partial differentiating sub-block divided in the flow direction. The advantages of this newly developed simulation platform are as follows; (1) Model is easily and rapidly constructed by putting and con-
necting blocks as if designing real system. (2) Fluid parameter such as density, viscosity, bulk modulus, inlet condition etc. can be easily changed through clicking block and setting the parameters. (3) It is possible to simulate unsteady flow, for instance, flow with the deformation of a elastic tube. The software of MATLAB/Simulink is utilized as the simulation platform.

**VARIFICATION OF SIMULATION**

First of all, we verified the performance of the model-based simulation platform. Figure 3 shows the comparison between simulation and experimental result about the flow-rate in each capillary (PEEK, inner diameter is 0.125 mm, length is 33 mm and 282 mm of each) depending on each pressure resistance. The connector blocks of a sudden shrinkage and a sudden enlargement, which also generate pressure resistance, were added to the model. The input flow were applied by motorized syringe-pump. The flow-rate was measured through checking the volume rate in a measuring cylinder. As shown in the figure 3(c), taking every element into simulation carefully, the simulation result shows good agreement with the experimental result in each flow-rate.

Figure 4 shows the evaluation of dynamic response after pump quickly starts to feed water into flow passage. The passage consists of elastic tube (TYGON®, inner diameter is 0.79 mm, outer diameter is 2.83 mm, tensile modulus is 4.5 MPa), capillary (PEEK, inner diameter is 0.125 mm, length is 150 mm, tensile modulus is 3.5 GPa), and residual air-bubble (~12 μL, calculated from experimental data). The pressure value was measured by using a pressure sensor (Keyence AP-43, the sensitivity measured through changing the head pressure applied at the sensor). The flow-rate of the pump increases to the set value \( = 3.33, 6.67 \mu \text{L/s} \) linearly for 0.5 s. However, at the start, the elastic tube begins to expand gradually and the residual air-bubbles begin to shrink gradually due to the pressure resistance in the capillary tube. Therefore, the pressure hysteresis curve were observed when starting and stopping. The deviation between the calculated pressure level and the measured one was less than 4 %. This simulation result predicts the transient flow of dynamic response very well.

Figure 5 shows the verification results about fluid flow driven by capillary force. Ethanol was used as a fluid and Teflon tubes (inner diameter is 0.3 mm and 0.5 mm) were used as capillaries. The value of surface tension of ethanol \( 2.29 \times 10^{-3} \) kg/m and the value of the contact angle of ethanol to Teflon; 41 degree were used for the simulation. A video camera took a moving image of the ethanol's meniscus with a ruler set along the capillary. A drop of ethanol was placed into a small well directly connected to the inlet of the capillary tube. The flow speed was obtained through calculating the moving rate of ethanol's meniscus. As shown
in figure 5 (c), The flow speed is initially high and gradually decreasing because the pressure resistance is increasing as the length filled with the ethanol is increasing. In addition, though the capillary force of thinner one (inner diameter is 0.3 mm) is 1.7 times as large as that of thicker tube (inner diameter is 0.5 mm), the flow speed of thinner tube is slightly smaller than that of thicker one. This is because that the flow resistance of thinner tube is more than that of the thicker tube. The simulation results trace these phenomena well.

APPLICATION

Figure 6 (a) shows basic configuration of paper-based analysis device (we call it "paper MEMS chip") and the micro-fluid circuit model corresponding to the channel network of the chip. Using this model, the performance of the capillary pump was evaluated. Figure 6 (b) is the comparison of the flow-rate between the capillary pump and a single capillary. In this case, driving liquid is water, the inner diameter of each capillary is 0.1 mm, and the capillary force of 98 Pa is applied in each capillary. The length of inlet-channel, 4-channels, and 16-channels is 3mm. The result shows, while the water flows in the inlet-channel, the flow-rate of the capillary pump is same as that of the single capillary, but, while the water flows into 4-channels and 16-channels, the flow-rate keeps higher level, because the flow-rate in the 4- or 16-channels becomes smaller and the pressure resistance of each channel reduces.

CONCLUSION

Model-based simulation platform for integrated micro-fluid circuit was newly developed. It enables us to form simulation model easily and quickly by connecting blocks corresponding to the fluid elements, and deals with transient, unsteady flow. The simulation platform predicts well static characteristics and dynamic response in micro-channels, and is now utilized to design new application - paper MEMS chip.

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REFERENCES


CONTACT

*R. MIYAKE, tel: +81-82-424-4372; rmiyake@hiroshima-u.ac.jp