Pneumatic Regulation of Bi-Directional Fluid Flow in Microchannels

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ABSTRACT

This paper presents a modeling of airflow inside micro-tunnel for fluid pumping. By utilizing unidirectional air servo system, fluid flow can be regulated within microchannels. The operation of servo system is controlled with multiple nozzles. Pressure variations lead to two fundamental operational modes: "suction" and "exclusion" in channels. Three-dimensional finite volume simulations are tested to demonstrate that operation mechanism for suction is via the generation of a reverse airflow, while exclusion is obtained without the reverse airflow.

Keywords: Pneumatic control, single direction airflow, two-way fluid flow, biochip.

1 INTRODUCTION

This paper describes details of a novel pneumatic method for regulating fluid flow in microchannels. Thanks to the advancing technologies of microelectromachanical engineering, many miniaturized devices can now be used in the area of biological and chemical analysis. State-of art devices include microchannels, micropumps [1-2], microvalves [3], micrometers, micromixers, micro thermal-cyclers [4], and micro optical detectors [5]. Many biological and chemical laboratory sample treatments such as capillary electrophoresis (CE), PCR, cell capture, registration, cell fusion, cell counting can be reproduced in these microdevices. These treatments are designated to amplify double stranded DNA [6], to separate DNA fragments [7-8], to identify cells of different kind [9-12], to sort out cells and to fusion them together, to break the cell membrane apart and extract inner material, or to detect bacteria [13]. And data show that these chip devices have proven with better and higher efficiency compared to bench-top equipment.

However, challenges remains when the issue comes down to integrating these discrete devices onto a single unit. That means that in order to achieve the ultimate goal of lab-on-a-chip (drops a small volume sample of whole blood in one end of the chip and we expect the targeted genetic sequence will be displayed on the other), many interfacial problems must be solved. Another critical issue is that handling of biofluid sample inside microchannel must be with great care to avoid alternating their chemical properties. Last but not least, is the issue of cost. Fabrication of micro-pumps, valves often requires complicated layout and deposition of metals thus demands more money.

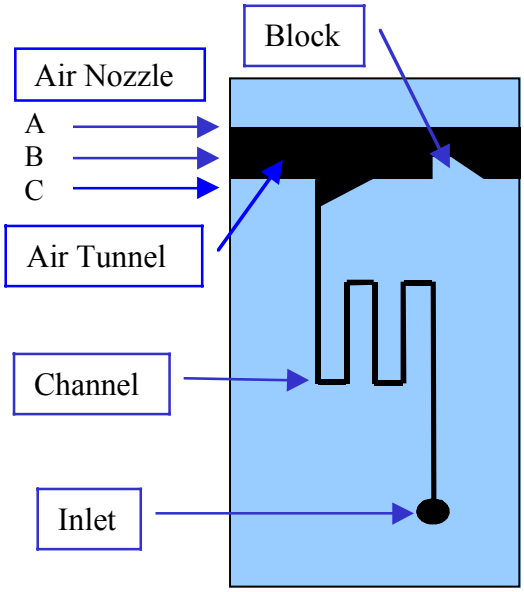
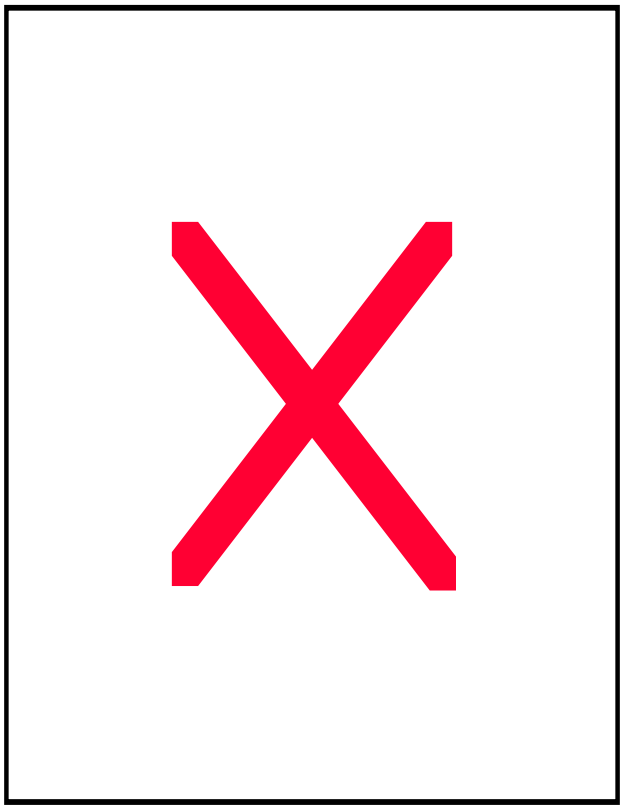


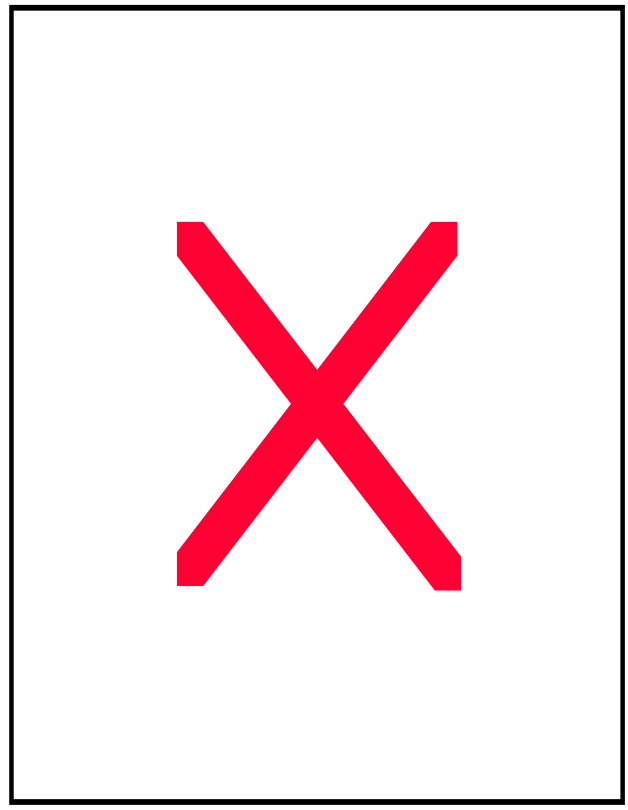
Figure 1. Device for bi-directional fluid flow regulation (modifies from reference [14]) . On top across the substrate is the air tunnel. The meander line represents a fluid channel. In the lower end of the channel is a reservoir for fl uid introduction.

In this short letter, we shall illustrate an effective, versatile, valuable and low cost method. This method adopts continuous mass transportation of air molecules inside micro-tunnel. Pressure variation in the tunnel allows one to control the direction of fluid flow. The physical mechanism is based upon the kinetic motion of the air molecules. Our preliminary experimental results demonstrate the feasibility. Its most distinguishing character is that a two-way fluid driving system can be easily achieved by varying the pattern of injection.

2 PRELIMINARY STUDY

Experimental details have been previously reported in reference 14. Briefly, the set up is a combinatory set of an air pump, a set of nozzle, a video camera and a minidevice. As shown in Figure 1,our device includes an air tunnel, a fluid channel, and a block. On top is the tunnel. In the center is the meander fluid channel, which is connected to the tunnel at a junction, denoted "T", with a total length of





170mm, 1mm wide and 1mm deep. In the lower end of the fluid channel is a reservoir in radius of 2mm for fluid introduction. Regulation of airflow to the tunnel is via nozzles (three to five) in parallel. The test piece of device is made of PMMA with an over all size 50mm wide, 100mm long and 10mm thick. The channel is fabricated by mechanical drilling, glue sealed with another piece of plastic on top. The experiment is operated as the following: first of all the airflow is set to choose a proper number of nozzles. Then an air block is positioned in the tunnel. After that sample fluid is loaded in the inlet, then a pressurized airflow is delivered into the air tunnel (10mmx1mmx50mm), and the motion of fluid is taped right away with the camera.

What we intend to study is the dynamical phenomena of the flow in the tunnel and its relation to the force acting on the fluid. Our results show that "suction" and "exclusion" of fluid can be achieved under the following conditions; when the central nozzle is open, the fluid is drawn; when all five nozzles were open, the fluid is repelled. We emphasize that all the measurements were taken carefully to eliminate the effects of surface tension and gravity.

Measurements of the suction force were tested with fluids with viscosity from low to high for water, PRMI, FBS, Blue Dyes, etc. Our results show that as the block position is moving downstream away from the junction, the suction force first increases then decreases. A maximum suction force was observed when the block is at a distance of ~ 5cm to the junction. For exclusion, the flow rate keeps increasing as the block is moving away.

3 MODEL SIMULATIONS

To understand the flow dynamics in the tunnel, simulation was conducted. The governing theories of our analysis are Navier-Stoke equations, i.e., and coupled nonlinear equations for continuity, momentum and energy conservation. The parameters used in our calculations are the geometrical size of air tunnel, with width W, height H and length L. According to the theory, the flow resistance vs tunnel area is nonlinear because of the generation of vortices in the XY planes. Accordingly if the channel area were shrink of by an order of magnitude that would increase the flow resistance by more than four orders of magnitude ~ 10^4.

An equivalent model is constructed based on numerical finite volume program (Star LT). As mentioned previously, the nozzle number used is three to five. For simplification, we shall illustrate the case with three nozzles only, denoted as A, B and C. The tunnel is meshed with hexahedral cells and each cell has eight vortex points in Cartesian coordinate. In order to be able to see fine variation of flow vector field, we refined (doubled or tripled) the cells around all boundaries, and the area of intersection. The parameters used in our calculations are: temperature of air at room temperature with a density of 1.205 kg/m and molecular viscosity 1.81×10^{-5} Pa s; inlet velocity of air for each nozzle from 2m/s to 20.0 m/s along the X-direction; turbulence k-ε

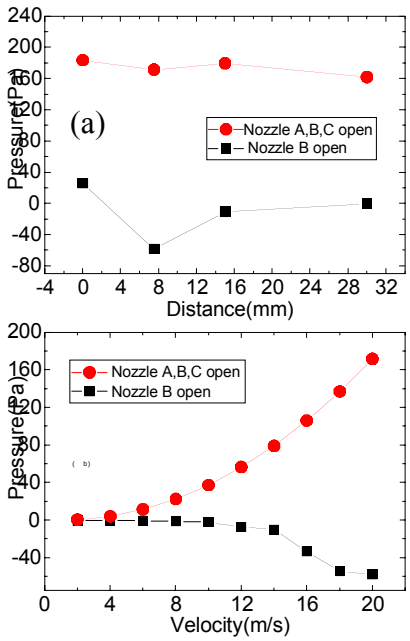


Figure 4. Pressure at the "T" junction. (a) is against block distance, and (b) is against inlet air molecule velocity for rectangular block with height H/2.

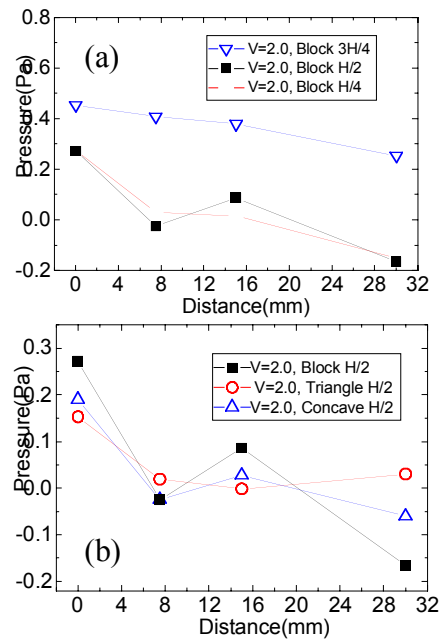


Figure 5. Pressure at the "T" junction. (a) is against block distance at inlet air velocity of 20m/s and (b) is vs inlet air molecule velocity.

model is applied and the boundary condition along the Z direction is symmetrical. To compare with the data, pressure at the junction is calculated as a function of the distance of the block to the junction, of the height of the block, of the block shape, and of the air inlet velocity.

4 RESULTS AND DISCUSSION

As shown in Figure 2, four different configurations of air injection are studied. When all nozzles are open (a), the air molecules flowing into the tunnel, reaching steady within half a second, then squeeze through the neck above the block (see Fig. 3(a).). Since the density of air molecules is quite uniform, there is not much of pressure gradient except close to the junction. Note that the velocity of the stream above the block ~ 40m/s is about twice that of the inlet velocity ~ 20m/s. For Fig. 2(b), when the central nozzle B is open, the stream somehow splits more seriously in front of the block (see Fig. 3(b). When nozzle C is open only (Fig. 2(c)), the air stream bends upward and pass through the block. When nozzle A is open (Fig. 2(d)), most of the air molecules go straightforward without hitting the block. Note that for mode ABC, Fig. 3(c), the pressure is very high at about +172 psi near the junction and the lowest point –551.2 psi is at the up front edge, i.e., stagnation point of the block.

For mode B, Fig. 3(d), the pressure profile is rather complicated, however a reverse airflow appears in front of the block. It is obvious that the generation of vortex is due to the block. A simple picture is this: when the central nozzle is opened, the main streamline splits into two parts. The major branch passing over the block and leaks out of the tunnel, while some of the airflow curves down and hit the block because of diffusion. The side branch thus generates a counter clockwise vortex flow. The reverse flow drags air molecules around the junction, pushing them backward to the front end and piled them up, then carry them into the main stream flow and leaking out. This phenomena is actually is working like a pump inside the tunnel. The pumping vortex perishes with the addition of the top and bottom streams, which force the pumping vortex moving to the block, and then diminish.

It is clear that the position of the vortex is crucial. As shown in Fig. 4(a) for mode ABC, when the block position is moving backward, the exclusion pumping force decrease monotonically. In contrast, the suction force exhibits a minimal of –60psi, at a distance of ~ 8cm. The pumping effects as a function of the air molecule inlet velocity are summarized in Fig. 4(b). For mode ABC, the exclusion force increases monotonically as the velocity increases, while the suction force shows a flat plateau in the low velocity zone then drops dramatically as the velocity is over ~12 m/s.

We also have studied the effects of block height and block shapes to suction force as a function of block position at a low velocity. As shown in Fig. 5(a), the overall behavior of pressure is quite different from that at a high velocity of 20m/s. Beside, when the height of the rectangular block increases from half to three quarter of the channel height H, the pumping pressure varies from

negative to positive at the position of 30mm i.e., from suction to exclusion. As to the change of block shapes, Fig. 5(b), it appears to have even more complicate effects. The behaviors of the concave and block are similar, while the triangle does not provide much suction force up to 30mm. All the above phenomena have to do with the generation of vortex. A comprehensive explanation of the above phenomena will appear elsewhere.

5 CONCLUSIONS

In summary, theoretically, we have built a numerical model to study the dynamics of airflow inside a tunnel. By changing the configuration of the flow injection as well as the displacement of a block, the air dynamics could generate positive and negative pressure zones. The model results are consistent with experimental results. With the connection of a fluid channel to these pressure zones, where the pressure is controllable, we can put these together into practical devices. These devices can be useful for biochemical, biological and chemical analytical tools. Yet, in the course toward miniaturization, our two-way flow devices still have to overcome the problems of surface tension when the channel sizes are reduced to micro ranges.

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