A Closed Device to Generate Vortex Flow using PZT

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***Abstract*- This paper reports for the first time a millimeter scale fully packaged device which generates a vortex flow of high velocity. The flow which is simply actuated by a PZT diaphragm circulates with a higher velocity after each actuating circle to form a vortex in a desired chamber. The design of such device is firstly conducted by a numerical analysis using OpenFOAM. Several numerical results are considered as the base of our experiment where a flow vortex is observed by a high speed camera. The present device is potential in various applications related to the inertial sensing, fluidic amplifier and micro/nano particle trapping and mixing.**

I. INTRODUCTION

Vortex flow which offers an efficient solution to create micro vortices is a potential technique to transport and then concentrate micro-particles into a predetermined location and to enhance the mixing of particles [1], [2]. For example, ion wind based vortex and asymmetric flow generated can be applied to increase the concentration of biological samples, shorten the cultivation time and detect the physical properties of the flow [3]–[6]. Vortices generated inside chambers were used to trap, collect and manipulate rare cell [7], [8].

As we know, flow in a closed system possesses several advantages, such as minimizing the number of analyzed samples and partial/complete freedom from the contamination by environmental variations [9]–[13]. With the introduction of circulatory flow, the integration and miniaturization of measuring systems significantly enhance the capability and impact of microfluidic systems [14]–[16]. The circulatory flow in a confined space is applied mostly in the inertial sensing and particularly angular rate sensing where the advantage of a self-contained valveless micro-pump reduces the risk of damage to mechanical counterparts [17]–[26]. The vortex based inertial fluidic system has been described in several publication [27]–[29].

While vortex flow has been played an important role in microfluidic systems, the techniques to create a vortex flow have either been represented incompletely or included only an external pump which is bulky and expensive. Thus, a self-package device generating micro vortex flow in a closed system will be studied and reported for the first time in this paper. A conventional PZT diaphragm is utilized to circulate a flow inside a closed system. A vortex flow with high velocity is observed and successfully investigated by both numerical simulation and experiment

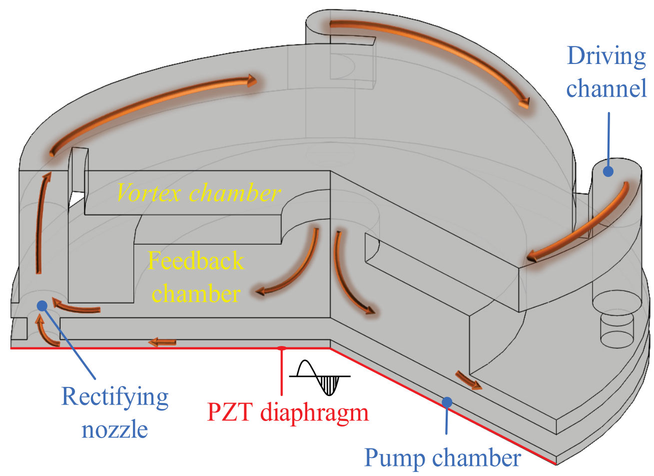

Figure 1. Mechanism of the present device. Arrows show the movement of gas flow which is initialized by a vibratory PZT diaphragm and rectified by nozzle; and moves from the driving channel to the vortex chamber.

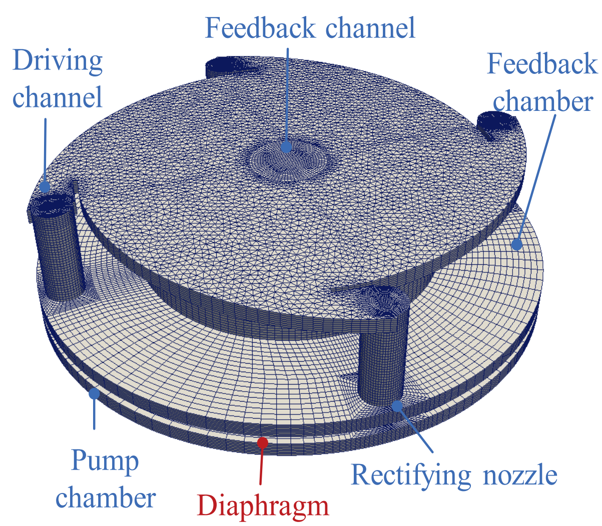

Figure 2. Decomposing the present device into structured mesh.

II. Design and Numerical Simulation

Consider the present designed device which includes a disc-cylinder whose dimensions are 20 mm (diameter) × 5.5 mm (length) with a pump chamber in one side and a vortex chamber on the another side as described in Figure 1.

The pump and vortex chambers are connected each other via four driving channels with a diameter of 1.5 mm each at the outermost edge of the cylinder. At the center, the cylindrical feedback chamber with a diameter of 3 mm is connected to the vortex chamber by the four connecting channels to form a rectifying nozzle.

The pump chamber is actuated by a PZT diaphragm which periodically vibrates under an applied voltage and makes the volume of pump chamber shrinking and swelling. Thus, the gas/air inside the chamber is alternatively expelled and sucked in each vibration cycle. Due to the rectification of the nozzle, a small net flow is generated inside driving channels in each cycle. The net flow propagates into the vortex chamber, circulates and then moves back the rectifying nozzle through a feedback chamber. The circulating flow together with its momentum dramatically amplifies the rectifying effect of the nozzle. After certain circulations, the velocity and also the momentum of flow reach values enough high to generate a vortex inside the vortex chamber.

The circulating flow in channel is governed by the following equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \quad (1)$$

$$\frac{\partial \rho \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\rho \vec{u} = -\nabla p + \nabla \cdot (\mu \nabla \vec{u}) \quad (2)$$

$$\frac{\partial \rho c_p T}{\partial t} + (\vec{u} \cdot \nabla)\rho c_p T = \nabla \cdot (\lambda \nabla T) \quad (3)$$

where $\vec{u}$, p, and T denote the velocity vector, pressure, and temperature of the flow field, respectively; $\mu = 1.789 \times 10^{-5}$ Pas, $\rho = 1.2041$ kgm^{-3}, $\lambda = 2.42 \times 10^{-3}$ Wm^{-1}K^{-1}, and $c_p = 1006.43$ Jkg^{-1}K^{-1} are the dynamic viscosity, density, thermal conductivity, and specific heat of gas, respectively. Since the working gas is air, the relationship between the pressure and density follows the state equation of an ideal gas $p = \rho R_u T/M_w$, where $R_u = 8.314$ Jmol^{-1}K^{-1} is the universal air constant and $M_w = 28.96$ gmol^{-1} the molecular weight.

Figure 2 presents the 3D model of the designed device together with its meshing for the simulation.

The boundary condition imposed on the diaphragm is derived from its vibrating rate $v(\vec{r}, t) = 2\pi f Z \cos(2\pi f t)\,\varphi(\vec{r})$ with the shape function $\varphi(r) = (1 - (r/a)^2)^2$, where a is the diaphragm radius and Z the center deflection of the PZT diaphragm. The transient solution is obtained by our program code developed in the environment OpenFOAM.

Numerical results by Figure 3 describe the velocity contour of the flow which depicts a vortex generated inside the chamber with a PZT diaphragm deflection Z of 20 µm (Figure 3b). Meanwhile if the deflection is not sufficient, the flow is sucked backward the feedback chamber shown by red arrows in Figure 3a and thus, no rotating vortex is created.

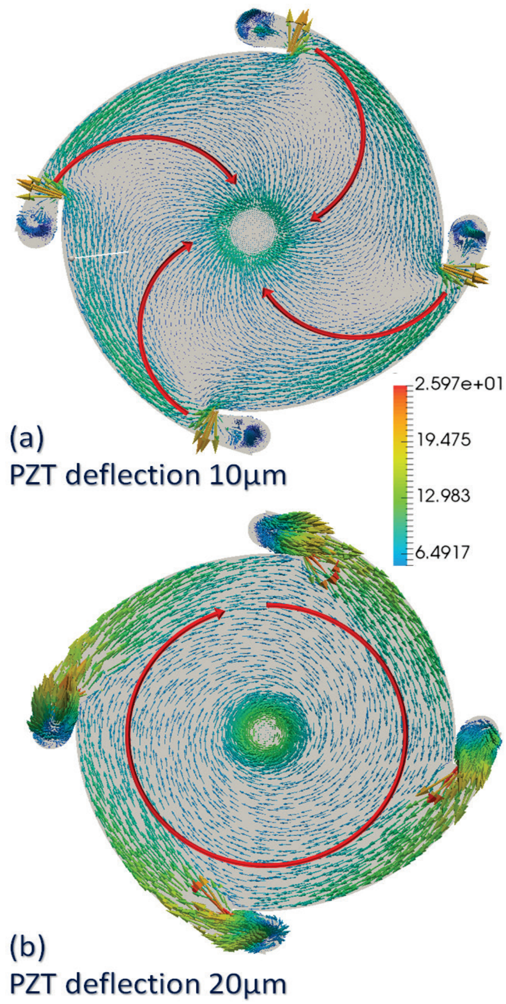

Figure 3. Numerical results of the simulation: Top view of vortex chamber without vortex by PZT deflection of 10µm (a) and with a vortex by PZT deflection of 20 µm

Let U_r, U_θ the components of the averaged velocity with time in a circulating cycle on the radial and azimuth directions, are given by

$$U_r(r) = \frac{1}{2\pi}\int_0^{2\pi} u_r(r,\theta)d\theta\,, \quad (4)$$

$$U_\theta(r) = \frac{1}{2\pi}\int_0^{2\pi} u_\theta(r,\theta)d\theta \quad (5)$$

where $u_r(r,\theta)$ and $u_\theta(r,\theta)$ are the radial and azimuth components of the local time-averaged velocity vector.

The U_r and U_θ with the radial distance (r) are presented in Figure 4. Their profiles are similar to those by a flow of a blob vortex and sink and can be approximated by

$$U_r(r) = \frac{K_r}{2\pi r}\left(1 - e^{-r^2/\epsilon_r^2}\right),\; U_\theta(r) = \frac{K_\theta}{2\pi r}\left(1 - e^{-r^2/\epsilon_\theta^2}\right) \quad (6)$$

where K_r and K_θ are constant and represent the strength of vortex; and ϵ_r and ϵ_θ the widths of the blob vortex and sink, respectively. In this work, K_r = 59.4 m^2/s , K_θ = 82.7 m^2/s, ϵ_r = 1.63 mm, and ϵ_θ = 0.75 mm, using the least square method.

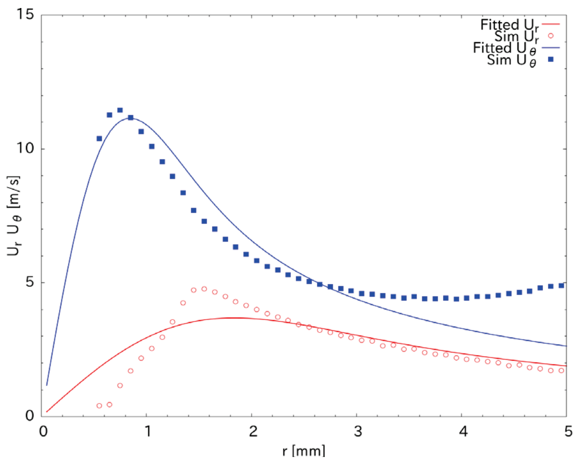

Figure 4 The variation of radial and azimuth velocities with the radial distance. The square and cycle symbols are simulation data and the solid lines are fitting data

III. Experimental Results and Discussion

A transparent prototype of the designed system as presented in section II and made of poly-methyl methacrylate (PMMA) is given in Figure 5. The system includes four tungsten hotwires (W-461057, Nillaco Ltd) with length of 2.4 mm and diameter of 10 µm each, which are set up inside the vortex chamber to characterize the flow. Lead pins (Preci-Dip) are installed in the device and work as hotwire holders.

In order to investigate the appearance of a vortex flow, particles suspended air is introduced in the device. Air flow is visualized via the motion of particles. Because the time scale for the particles' motion in the main chamber is in the order of milliseconds, a high-speed camera, triggered by the power source of PZT membrane, is set up on the top of the device to capture the air motion (see Figure 4).

Figure 6 are the snapshots of the trace of particles at several times (200, 220, 240, 250, 260, 270, 280 and 290) µs. The figure proves the appearance of a vortex flow in the designed device as predicted by the numerical simulation in section II. A higher-resolution video is also recorded as a supplementary material and depicts that flows from the outlet of four driving channels are almost similar. Moreover, the vortex flow created is almost symmetrical in the vortex chamber. With hotwires already installed , the device is ready for the inertial sensing application and will be reported soon.

IV. Conclusion

A millimeter scale fully packaged device which generates a vortex flow of high velocity is reported. The flow actuated by a PZT diaphragm whose velocity increases after each circulation forms a vortex in a desired chamber. The design of the device is firstly conducted by a numerical analysis whose results are referred as the base of the experiment. Experimental results are in good agreement with our numerical prediction and a flow vortex is observed by a high speed camera. Both the numerical and experimental results demonstrate the potential of the device in various applications related to inertial sensing, fluidic amplifier and micro/nano particle trapping and mixing.

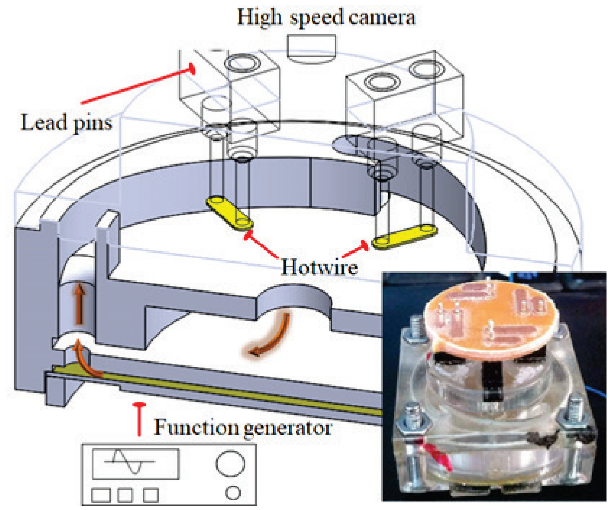

Figure 5 A schema of the designed device. Inset shows a photo of the device. The PZT diaphragm is assembled underneath and the lead pin is on top.

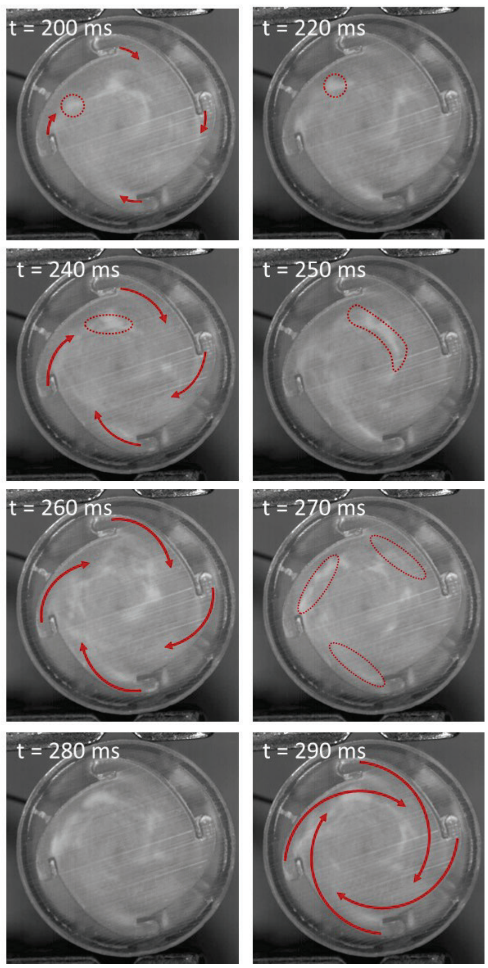

Figure 6. Flow of particles observed inside the device by a high speed camera. Vortex flow of particles is observed inside the vortex chamber by solid arrow. Dot lines indicate a redistribution of particle clusters by the vortex

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