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A New Vortex-based Device Using Dragonfly Wing to Reduce the Chip Size

Pang-Lun Wang[1], Jhih-Syuan Ciou[1],
Lung-Jieh Yang*[1], Yung-Chiang Chung[2]
Niroj Kapri[3], Balasubramanian Esakki[3]

[1] Tamkang University, Tamsui, New Taipie City, Taiwan
[2] Ming-Chi University of Technology, Taishan, New Taipie City, Taiwan
[3] Vel Tech University, Avadi, Chennai, India
*Corresponding author; Email: LJYANG@mail.tku.edu.tw

***Abstract*- This work presents a new vortex-based flow device. A corrugated dragonfly wing blocks in a microchannel of 250 µm wide good to capture particles and to reduce the chip size. Two conclusions have been found. The new flow chips made of PDMS and their microbes filling experiments firstly revealed that only one dragonfly wing in the channel works in particle capture but without choking. Secondly, COMSOL-Multiphysics simulation of the new design using dragonfly wing predicted that the reduced entrance channel length by 50% was achieved by adding a dragonfly wing to the previous design by Sollier. This new design of vortex-based devices is good for the integration and application for tumor cell collection, capture and sorting in the future.**

Keywords: Vortex-based device; dragonfly wing; particle capture

I. INTRODUCTION

The size selective collection capturing and sorting of particles using vortex based microchip technology are important in recent year [1-3]. From these previous design of the "vortex based" microchips, some downstream square grooves are distributed along the side walls to create vortex flow patterns. A long straight channel in the upstream entrance region is constantly necessary to give particles tendency to run towards the grooved sidewalls. So it is much easier for large particles to be trapped in the downstream square grooves with vortices. In this work the authors novelly inserted the dragonfly wings into the upstream entrance of a microchip to replace the long stretch channel. The simulation of particle flow tracing module of COMCOL Multiphysics, a CFD (computational fluid dynamics) software is necessary to the design of the new vortex based flow chip. CFD is an important technology of fluid mechanics is the past several decades. It used numerical method in computer control to solve the Navier-Strokes equation of fluid mechanics, which can predicted the flow field there are a variety commercial CFD software available, such as FLUENT, CFD-ACE+ (CFDRC), Pheonics, CFX and Star- CD.

This new design would like to use dragonfly wings effectively to shorten the chip size apparently, but even to be compared to the capture particles as Sollier's work [3]. Dragonfly wings don't have smooth surface contour but have complicated corrugated wrinkles. The steady flow field of this particular geometry can have vortices created inside the corrugated grooves or wrinkles and winkles and has been verified realistically by some flow visualization experiments [4-5]. Profile-folded construction of the dragonfly wing has a significant weight reduction effect on flying insects. In other words, dragonfly wing shape is a one dimensional, linear, zigzag wing winkle inducing "equivalent aerodynamic force" as the general two-dimensional teardrop-like solid airfoil. Many vortices in the corrugated grooves globally circulate a virtual boundary with geometry like a solid airfoil.

In this work the authors instead of using dragonfly wing in weight reduction of doing the flight mission, but try to miniaturize the dragonfly wing into microscale size. It's integrated into a microfluidic chip, and to make the most of its function about the vortex generation.

Dragonfly wings use the shear stress gradient change of the flow next to the microchannel to produce eddy vortex in the corrugated groove or cavities. With balancing the shear stress gradient and the inertial force in microfluidic flow, the particles of different diameters have their respective equilibrium positions in the microchannel. When the bigger particles enter into the dragonfly wing region, their shear stress induced force overcomes the inertial force. Therefore these particles are pushed into the wing cavities, the pre-existing vortex area with low local pressure. So the dragonfly wing could filter particle with specific size promisingly.

For the application of aircraft wings, a flow field with high enough Reynolds number (***Re***) in necessary to generate vortices in dragonfly wing. Tamai et al. [5] used PIV to verify experimentally that the ***Re*** is about 34,000 to successfully induce vortices on a dragonfly like the case in Fig.1. Such a high ***Re*** flow provides enough energy to overcome the adverse pressure gradient in the surface boundary layer, and to prevent flow separation and aircraft stall. In Fig. 1, simulated by COMSOL Multiphysics herein, it is obvious that many eddy vortices generated in the cavities along the wing surface, showing the same nature as described in the literature [4-5].

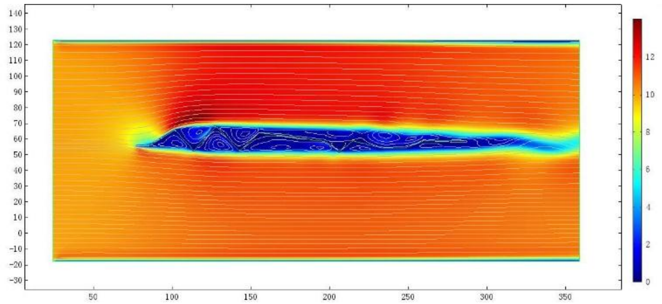

Fig. 1. Simulation of the flow of the dragonfly wing by COMSOL Multiphysics

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However Re=34,000 is almost impossible to be implemented in a microfluidic flow chip with the total size of several mm. The next curious key is to find how small Re is even feasible in the micro flow chip to generate vortex as the macroscopic case in aircrafts.

In Ref. [3] and Fig. 2 the vortex-based technology using to filtrate or capture CTCs (circulating tumor cells) is with a relatively simple groove configuration along a straight channel. The inflow pipe/channel length $\boldsymbol{L_c}$ is 4 mm and the channel width $\boldsymbol{W_c}$ is 40 μm. The dimension of a cavity groove is $\boldsymbol{W_R} \times \boldsymbol{L_R}$=480μm×720μm. One pitch of a cavity groove including its entrance is 1000 μm. So the working fluid inside can keep its stability.

For the nomenclature defined in Ref. [3] and Fig. 2, $\boldsymbol{X_{eq}}$ is the balance seat which denotes the position distant from center line for particles to take equilibrium between the wall shear stress and the inertial momentum of particles. $\boldsymbol{X_{eq}}$ is strongly related with the particle diameter $\boldsymbol{a}$ to channel height $\boldsymbol{H}$ ratio. Base on the previous observation, the bigger the particle diameter $\boldsymbol{a}$, the closer the particles to the wall (the larger $\boldsymbol{X_{eq}}$). Such a correlation allows the grooved channel to filter out particles of different size. For the channel array with 50 μm gap it can totally gain 50% of bigger (tumor) cells, a relatively high efficiency case claimed in Ref. [3].

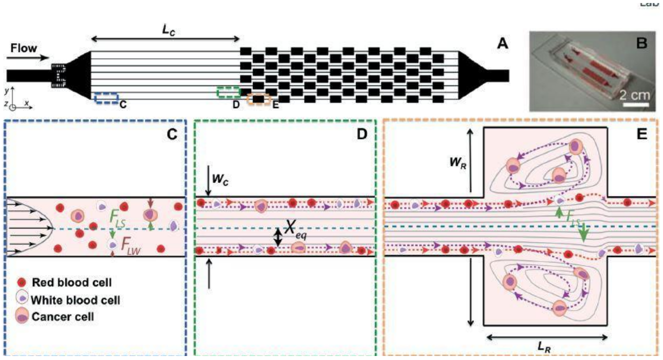


Fig. 2. Size- selective collection of circulating tumor cells (CTCs) using vortex technology [3].

The fact how the dragonfly wings have the function to conduct particles towards the side walls of a micro channel, or even towards to the downstream grooves, needs the corresponding particle filling experiment and the particle flow simulation by COMSOL Multiphysics herein. The configuration of a similar but micro-scaled dragonfly wing shown in Fig. 1 is as below.

- Wing chord (from leading edge to trailing edge): 806 μm;
- Line/wing rib width: 20 μm ;
- Intel angle of attack: 50° - 60°;
- Wing thickness-to-chord ratio: 122/806= 15%

The relative coordinates of the turning points on the dragonfly wing is referred to Refs. [4-5]. The inlet velocity, equivalent to Ref. [3], is selected as 0.52 m/s so as to have the corresponding $\boldsymbol{Re}$ approaching to 419, far away from the $\boldsymbol{Re}$=34,000 in the aircraft case [5].

Another fundamental difficulty of this work is to design a new flow chip with proper dragonfly wing configuration, and to assign its appropriate flow speed for generating the necessary vortices in the micro-scale corrugated grooves along the wing. At first, the design of the dragonfly wing structure was to capture the particles. From the actual situation, the structure of the dragonfly wing micro-flow channel will produce two different flow rates. At the upper and lower halves of dragonfly wing, the pressure will be uneven. From the simulation results of Fig. 1, it is expected that the particles flow through the dragonfly wing structure will move closer to the two side walls of the micro channel. We need to perform the real experiment and the flow simulation of new flow chips with dragonfly wings, and hoped to lead to a good convergence of better percentage of particle capture rate for applications in the future.

II. PDMS MICROCHIP AND PARTICLE FILLING EXPERIMENT

PDMS soft lithography using SU-8-2050 resist is good to investigate the flow pattern of a microchip with a dragonfly wing micro structure. The process flow of MEMS fabrication is shown in Fig. 3 which process details are omitted. The channel width and height are designed as 250 μm and 80 μmm respectively. For performing a particle filling experiment accordingly, the authors selected microbeads (Silia Flash 60 or Silicycle Model: R10010B) with diameters ranging from 1-20 μm, and observed the particle flow by a laser scanning confocal microscope (LSCM; LEXT OLS4100, OLYMPUS).

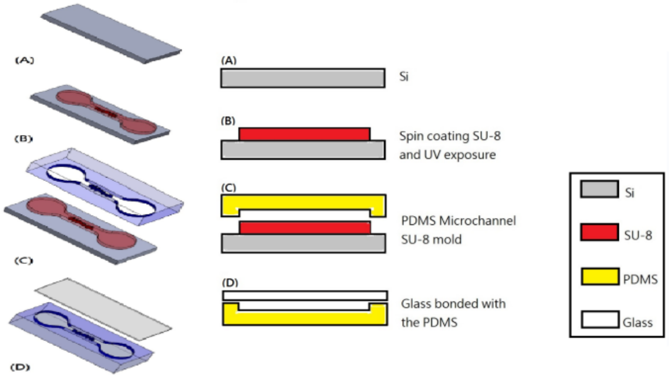


Fig. 3. PDMS MEMS fabrication for the flow chips with dragonfly wings.

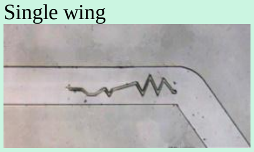
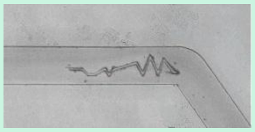
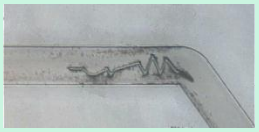
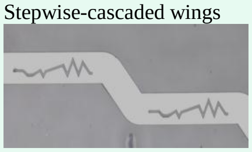
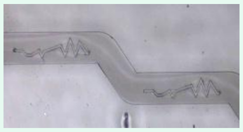
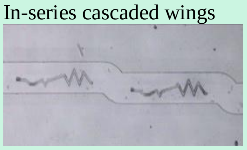
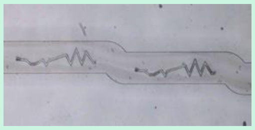
3 kinds of PDMS flow channels with single wing, stepwise-cascaded wings and in-series cascaded wings were used. The dilute way of microbeads is using 0.02 g in DI water of 1.5 c.c. As pumped by a syringe with the volumetric rate of 624 μL/min, the authors collected the flowing images in Table I. All PDMS channels captured microbes along the side walls after 3 mins of starting filling.

For the single dragonfly wing case, no choking of microbes occurs. However, serious choking of microbes can be observed for two cascaded wings is after 4-9 min filling. This experiment summarized that only one dragonfly wing blocked in the flow chip design is without choking.

III. COMSOL-MULTIPHYSICS SIMULATION OF THE NEW MICROCHIPS

Fig. 4 shows the new design of the vortex-based flow chip. Only one dragonfly wing assigned at the entrance to push particles toward side walls and downstream grooves. With different L values, the particle capture percentages changed as well. The COMSOL-simulated values of capture rate by COMSOL-Multiphysics are shown in Table II. The case of L=2mm shows the better capture capability than the longer case L=4 mm. In this COMSOL simulation, the particle size is averaged as 10 μm as their experimental size ranged from 1-20μm.

Table I. Micro-silica microspheres attached to the flow walls.

Flow channel type	Start capturing	Cluster capturing	Channel choking
Single wing 	03:00 	12:00 	No choking
Stepwise-cascaded wings 	03:20 	04:24 	04:24 
In-series cascaded wings 	03:40 	06:14 	09:38 

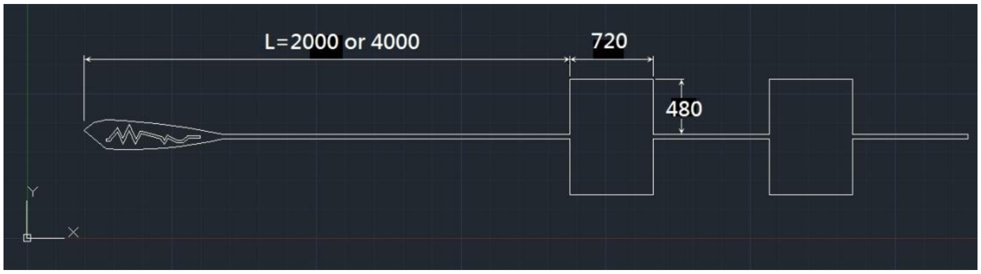


Fig. 4. The new microchip design using dragonfly wing

Fig. 5 shows the COMSOL simulation results of 10μm particle flows and their particle attachment. In Fig. 5(a) with a wing rib thickness of 20μm in this work, 10μm particles attached to both the wall and the wing head. It is quite different from the result of Ref. [6] or Fig. 5(b) with no wing rib thickness, which particles attach inside the dragonfly wing.

The authors also simulated the flows of the new chip design in Fig. 4 and compare the particle capture rates with Ref. [3] or Fig. 2. The data are summarized in Table II. Firstly in Ref. [3], there is no clear mentioning how many downstream square grooves are truly in their experiment. The authors have ever tried 1-8 grooves of Fig. 2 and found that 3-groove case is the best one with 6 % capture ratio per channel. Meanwhile the authors simulated the new design of Fig. 4 with two cases of 4 mm and 2 mm about the upstream entrance channel length. The case of 4 mm is also close to the dimension of Soiller's design [3]. Finally the authors found that the shorter entrance case of 2 mm is better than other cases. Not only its capture percentage is the best one of 9 % per channel, but moreover has the merit of shorter chip size.

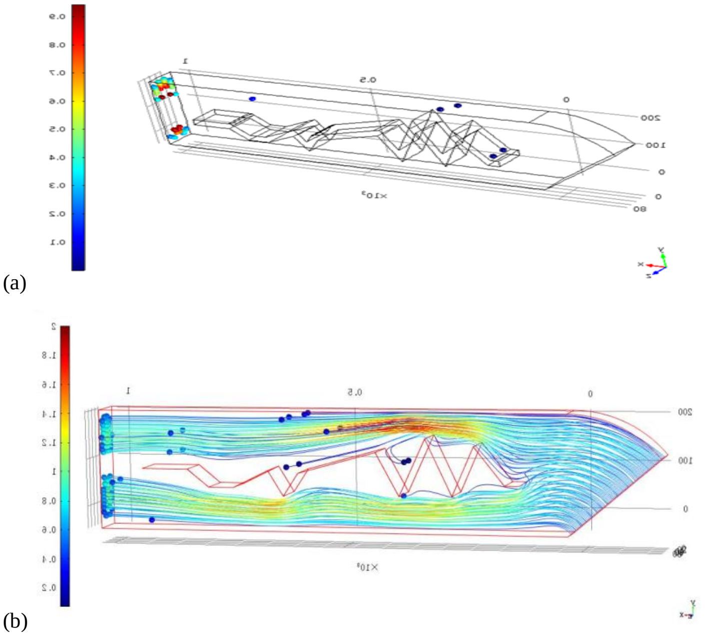


Fig. 5. COMSOL simulation of 10μm particle flow over a dragonfly wing: (a) wing rib thickness of 20μm in this work; (b) no wing rib thickness in Ref. [6]

TABLE II. CAPTURE PERCENTAGES OF DIFFERENT CHIP DESIGNS

Chip design	The 1st groove	The 2nd groove	The 3rd groove
Sollier [3]	0	0	6 %
L=4mm	0	0	0
L=2mm	0	0	9 %

IV. INCLINED ANGLE EFFECT ON DRAGONFLY WING CHIP

The flow field mentioned in a bending flow channel will produce some subtle changes, and this change will help us to filter out the particles [7]. In addition, Ref. [5] concluded that the inclined angle of 50° at the channel entrance can provide enough initial vorticity strength beneficial to the particle capture rate of 4% per dragonfly wing structure. Because the authors herein have adapted this conclusion of inclined angle effect and applied to the previous simulations in Table I and Figs 4-5, Some discussion about the inclined effect on the dragonfly wings is necessary.

Different inclined angle on dragonfly wing flow will induce different strengths of vortices in the following wing corrugations. For the dragonfly wing of aircrafts in the external flow, the larger inclined angle or the angles of attacks, the bigger the lift force for supporting aircrafts. Relatively, inclined angle at different values in the microfluidic channel herein are surely for bending the flow pattern which is good for particle capture. However, it’s hard to expect the optimum inclined angle herein unless by simulation in advance. Again, by the COMSOL simulation of different inclined angles ranging from 30° to 60° in Fig. 6, people can figure out which case is better by (1) judging how often the stagnation/vortex regions appeared in the channel; and by (2) counting the number of captured particles. It’s found that 50° case in Fig. 6(c) and 60° case in Fig. 6(d) have the better stagnation flow condition for capturing particles. Moreover, the 50° case in Fig. 6(c) captures more particles than the 60° case in Fig. 6(d).

V. CONCLUSITION

In this study, the authors developed a particle-captured device based on the vortex generation by dragonfly wings. Some conclusions are addressed as below.

1. With proper design of the new flow chip, the entrance channel size can be reduced 50% compared to the design in Ref. [3].
2. With the very low ***Re*** of 419, many vortices successfully appeared in the micro flow field of dragonfly wing channel by COMSOL simulation.
3. From the particle filling experiment, particle attachment happens for all the dragonfly wing channels after 3 min. One dragonfly wing in the channel works well without particle choking in the final.
4. By COMSOL simulation, the new flow chip design is claimed to have a better performance than Ref. [3].

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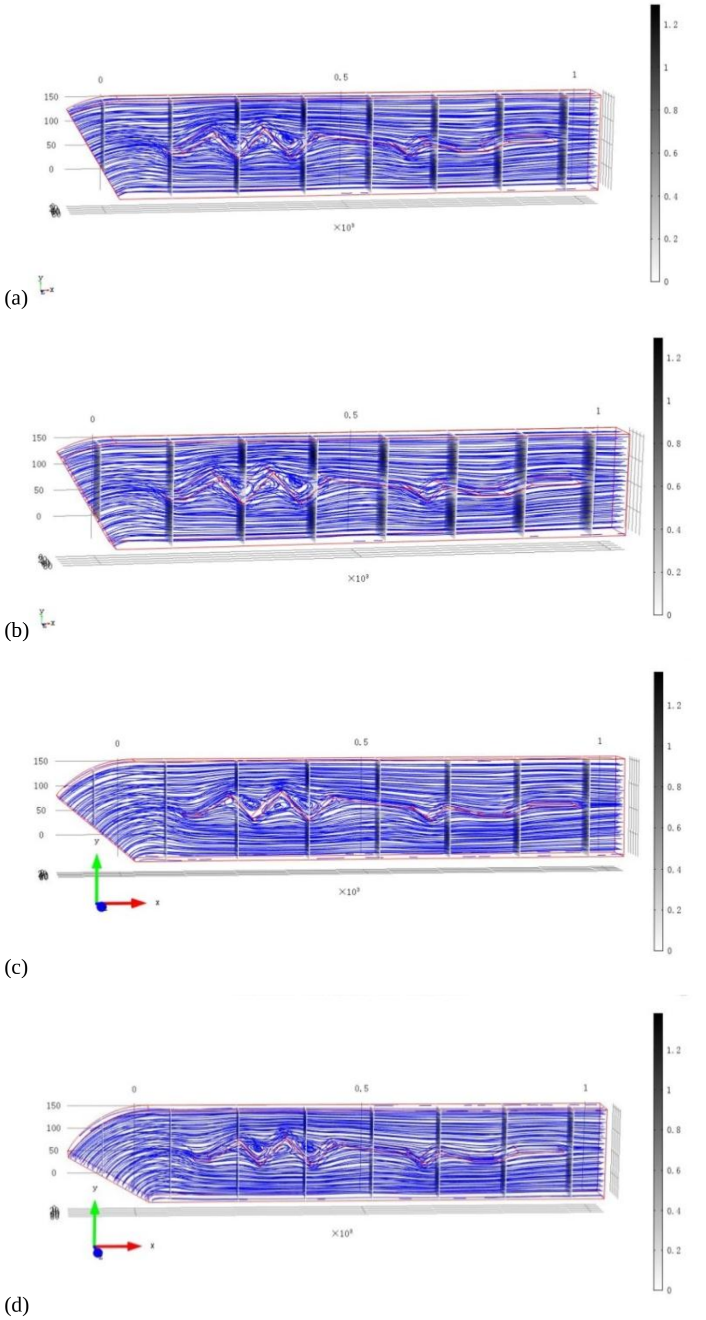

Fig. 6. COMSOL simulation of checking the effect of inflow angle-of attack: (a) inflow angle =30°; (b) inflow angle =45°; (c) inflow angle =50°; (d) inflow angle =60°.