Virtual vortex gear: Unique flow patterns driven by microfluidic inertia leading to pinpoint injection

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(Received 28 March 2018; accepted 6 June 2018; published online 20 June 2018)

An interesting phenomenon that vortices are sequentially generated on a microfluidic chip is investigated in this paper. The direction of every two adjacent vortices is opposite to each other, like a set of gears, and thus is named virtual vortex gear (VVG). Both experiments and computational simulations were conducted in order to make clear the mechanism of VVG. The experimental results show that only the flow from a particular point would form vortices and enter the target chamber. A technique of inverse mapping is proposed based on the phenomenon and it demonstrates that only a pinpoint injection is sufficient to control the contents of a microfluidic chamber. VVG can significantly reduce the volume of chemical usage in biological research and has potential for other on-chip applications, such as mixing and valving. *Published by AIP Publishing.*
<https://doi.org/10.1063/1.5031082>

I. INTRODUCTION

Lab on a chip (LOC) system has rapidly grown in the last few decades due to its unbeatable advantages of high-throughput, contamination-free, and requiring only a small volume of samples.^{1–5} Vortex is one of the key techniques for performing on-chip operations, such as cell trapping^{6,7} and flow control.^{8–11} Although vortex is generally difficult to be generated in the regime of laminar flow in a microfluidic system due to low Reynolds number, many studies show that vortices can still be formed when the Reynolds number is over a few hundred. In this work, we proposed a new mechanism of vortex generation where multiple vortices can be sequentially generated with the increasing of flow speed. The rotational direction of every two adjacent vortices is opposite to each other, like two connecting gears. Therefore, the phenomenon is named as “virtual vortex gear (VVG).” Such sequential vortices can be used as a tool for controlling contents in a microchamber, mixing different solutions, and a virtual valve in a LOC system.

Figure 1 shows an overview of the VVG where Figs. 1(a) and 1(b) are an experimental image with indications of flow directions and an illustration of gear analogy, respectively. The observation of VVG is first reported in our recent report and the mechanism is believed due to the inertia of the flow inside the channel.¹² In Fig. 1(a), the flow labeled 1 is the main flow from the upstream on upper-right side. Flow 1 experiences a sharp turn due to the channel geometry and hits the channel wall before splitting into two sub-flows. The split flow labeled 2 flows to the left of the figure and then soon splits again forming flow 3 which generates the vortex in the neck channel. Eventually, the flow 4 is split from flow 3 and three vortices are formed from the main flow 1. In other words, when the speed of the main flow 1 is high enough, multiple vortices will be formed and the direction of these vortices will rotate like paired gears as shown in Fig. 1(b).

The advantage of using VVG is that it provides a simple and robust way for on-chip mixing and concentration control. The feature of VVG can be applied in many different

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FIG. 1. An overview of VVG. (a) An experimental image of VVG with indications of vortex flows. (b) An analogy of a gear set for VVG.

microfluidic applications. For example, we can adjust the composition inside the chamber in Fig. 1(a) by VVG. The vortex of flow 4 appears if and only if the speed of the main flow 1 is high enough. Otherwise, the chamber area would remain a stagnation zone of the flow. As a result, the flow can be controlled to enter or not enter the chamber by controlling the flow speed. If there were cells culturing inside a chamber, the feature is convenient for controlling the amount of nutrition, or drugs, by VVG and is convenient for quantifying the response of the cells. Such a control cannot be achieved using on-chip system with continuous perfusion of culture medium. In general perfusion system, the flow rate needs to be carefully controlled otherwise it may be greater than cell adhesion force to the substrate and can washout cells. Another example is that we can do on-chip mixing using VVG since vortices are always very effective for mixing.¹¹

In addition to presenting the phenomenon of VVG, we also investigated different locations of the stream and their corresponding flow patterns in VVG. Before conducting the experiments, we first used computational fluid dynamics (CFD) software to test the patterns of the flow. To our surprise, only stream from a pinpoint on the cross-section of the fluid source would generate those vortices. In order to verify the simulation results, we conducted experiments with a VVG channel using three flow inlets. Different colored flows were simultaneously drawn into the main channel from these three inlets and a sheath flow was formed. The location of the streamline is manipulated by controlling the pressure balance of the two sheath inlets and the pattern of the stream can be directly observed in experiments. According to the results, we found that the location of the stream going into the chamber is from a pinpoint on the source cross-section, the cross-section of the main channel close to the inlet of the flow. The location and width of the pinpoint are measured based on the results.

Microfluidic vortex has been generated by different methods and applied in various applications.^{8–11,13–25} For example, Shang *et al.* generate microfluidic vortex with a piezoelectric (PZT) actuator and are able to control vortex size by adjusting the applied voltage.^{13,14} Park and Wereley use non-uniform alternating current electric field together with a laser beam to generate twin opposing microvortices.⁸ Haller *et al.* utilized microfluidic bar structure for generating vortex for plasma-cell separation.¹⁰ Sollier *et al.* fabricated a vortex chip to trap circulating tumor cell from a blood draw.²⁶ Wang *et al.* performed microfluidic mixing using electrokinetic vortex flow by both direct current and alternating current.¹¹

We have been investigating VVG since the first discovery of the phenomenon in 2017.¹² The dependency of the vortex size on the driving pressure was studied by a feedback control of driving pressure²⁷ and was followed by the image-based reconstruction of the three-dimensional flow pattern at the neck channel.²⁸ Here in this work, we focus on the flow patterns of streams from different locations and show that only the flow from a particular pinpoint would form the vortices. Such a pinpoint injection is first shown here and is convenient for controlling the contents of microfluidic chambers in applications.

The rest of this paper is organized as follows: The experimental method and results are in Secs. II and III, respectively. A technique of inverse mapping for pinpoint injection is introduced in Sec. IV. Discussions on the formation of VVG using different channel designs are presented in Sec. V. Finally, the conclusions are in Sec. VI.

II. METHOD

Both experiments and computational simulations were performed to test VVG for the flow patterns. The setups of experiments and simulation environments are explained in this section.

A. Experimental system

Figure 2 shows two different experimental setups, where Figs. 2(a) and 2(b) are the setups for observing VVG under different driving pressure and visualizing pinpoint injection, respectively. Both the experimental setups include a microfluidic chip, a syringe, a digital camera (IDP, Photron Co.), and a microscope (IX71, Olympus Co.). For visualizing the fluid flow, water-bead solution is prepared by mixing microbeads (4009A, Thermo Scientific Co.) and deionized water. The density of the microbeads is compatible with the water and the diameter of them is only $1\ \mu\text{m}$, so it is assumed that the flow characteristics would not be affected by the microbeads. VVG is observed in the red-dotted circles in Fig. 2.

The setup for the VVG formation is shown in Fig. 2(a), and the flow in the channel is generated by a constant pressure applied at the chip inlet. The pressure is regulated by a feedback controller, which is programmed on a computer, and its input and output are the pressure measured by a pressure sensor (FP101A, Copal Electronics Co.) at the syringe outlet and the speed of the pump movement, as x shown in Fig. 2(a). The value of driving pressure can be controlled and maintained as specified.

FIG. 2. Two experimental setups for VVG mechanism and pinpoint injection experiments. (a) A feedback-control pressure source is applied at the inlet and VVG is observed in the red-dotted circle. A photo of the system is shown below. (b) Flows from three inlets are simultaneously drawn into the microfluidic channel for manipulating the location of central flow. VVG is observed in the red-dotted circle. A photo of the system is shown below.

The experimental setup for the pinpoint injection is shown in Fig. 2(b), there are three inlets, and they are connected to two different reservoirs. One reservoir contains a water-bead solution and the other having colored water in it. A syringe pump is connected to the outlet for providing a negative pressure to draw flows from the reservoirs through the three inlets. The colored water and water-bead solution are drawn into the microfluidic system through the two side inlets and the central inlet. The colored water is for forming the sheath flow, while the water-bead solution is sandwiched by these two side flows. The location of the water-bead solution can be adjusted by changing the balances of the two side flows and is used for testing the flow pattern of the streams from different locations at the inlet. By pinching one side of the tube of the sheath flow, as shown in the upper-right corner of Fig. 2(b), the flow resistance would be altered, and as a result, the location of the water-bead stream would be changed due to different sheath flows, as shown on the right of Fig. 2(b). Figure 3(a) shows the mechanism of tube pinching, and Figs. 3(b)–3(e) are the location of the central flow under different sheath conditions.

There are two main considerations of flow control of multi-inlet channel from the outlet in Fig. 2(b) instead of the inlet in Fig. 2(a). One is that it requires only one syringe pump to manipulate the 3-inlet and 1-outlet system shown in Fig. 2(b). The other advantage is that it keeps the outlet at a stable low pressure, so the flow from the three inlets would always towards the outlet. Otherwise, the flow may direct from one inlet to another inlet, and very precise controls of three inlet pressures are necessary.

Figure 4 shows the dimensions of the microfluidic system. The width of the main channel, the width of the neck channel, the diameter of the chamber, and the turning angle of the main channel are $135\ \mu\text{m}$, $60\ \mu\text{m}$, $320\ \mu\text{m}$, and 150° , respectively. The microfluidic chip is fabricated by casting polydimethylsiloxane (PDMS) onto a mold made of photoresist SU8-3025 on a silicon wafer. The mold is developed by the standard photolithography process where the photoresist is first spin-coated on the silicon wafer and developed after the channel design is plotted on the photoresist through a maskless exposure apparatus (PLS-1010, PMT Corp.). Three main steps for casting PDMS are mixing of PDMS and its curing agent at the ratio of 9:1, degassing by putting the mixture into a vacuum chamber, and baking for cure.²⁹

B. Computational simulation environments

The simulation is performed using commercial software Autodesk CFD 2018 (Version 18.0, AUTODESK Ltd.). The simulation conditions are based on the actual experimental setup and the channel dimensions are the same as in Fig. 4, except that three inlets are replaced by a

FIG. 3. The pinching mechanism for pinpoint experiment. (a) An actual photo and a diagram showing how the flow resistance of the tube is adjusted. (b)–(e) Different flow patterns when the screw is turned at the angles of 0° , 22.5° , 45° , and 67.5° .

FIG. 4. The dimensions of the microfluidic design where VVG is formed. The upstream flow passes through a 150° turn and vortices will be generated, if the Reynolds number is large enough. The last vortex will be generated inside the circular chamber.

single inlet in the simulation. Three-inlet sheath flow is not necessary for the simulation since CFD can directly calculate the flow pattern of streamlines at specified locations. The pressure drop between the inlet and outlet is set as 100 kPa.

III. RESULTS

A. VVG mechanism and Reynolds numbers

The first part of the experiment is to visualize the formation of VVG and the corresponding Reynolds number at different phases. The inlet is connected to the pressure source, which is feedback controlled by a syringe pump, and the outlet is open to the air as shown in Fig. 2(a). The absolute driving pressure between the inlets and the outlet is ranged from 110 kPa to 200 kPa. Microbeads are used as the flow indicator for vortex observation. Figure 5 shows a step-by-step formation of three vortices captured in an experiment. For improving the readability, representative flow lines are shown by dashed lines in Figs. 5(a)–5(e), and each step is explained as follows. When the flow speed is relatively low and Reynolds number is less than 10, the streamline shown in Fig. 5(a) is parallel to the channel wall and stagnation areas are formed in the chamber as well as the edges of the corner. When the flow speed gradually increases, the streamline would be slightly distorted at the turning corner due the inertia of the fluid, as the dashed line shown in Figs. 5(a) and 5(b). When the speed is high enough, the

FIG. 5. The mechanism of VVG is introduced by a step-by-step vortices formation with increasing flow speed. (a) When the flow speed is low and Reynolds number is less than 10, the streamlines are parallel to the channel wall. (b) When the speed increases, the streamline is gradually distorted due to the inertia effect. (c) The distorted flow eventually hit the wall and split into two with the increasing speed. Flow 2 forms the first vortex. (d) When the flow speed is getting higher, flow 2 also splits into two, and flow 3 forms the second vortex. (e) The third vortex is eventually formed by the split flow 4 when the flow speed is high enough to have flow 3 split. (f) The experimental results of the relationship between the driving pressure and corresponding Reynolds numbers.

distorted stream would hit the channel wall and results in two split flows, as the flows 1 and 2 shown in Fig. 5(c). The flow 2 forms a vortex due to geometrical constraints at the turn area, while flow 1 directly goes to the downstream right after the turn. Figures 5(d) and 5(e) demonstrate the formations of two other vortices when the speed is getting higher and higher. The same mechanism drives the splitting and whirling of the flows. The reversal in the vortex direction can also be explained from fluid continuity that if one vortex is generated in a clockwise direction, the adjacent fluid will rotate in a counterclockwise direction and so on.

Figure 5(f) shows the estimated Reynolds number in the formation test. The Reynolds number is estimated using the equation

$$Re = \frac{uL}{\nu}, \quad (1)$$

where Re , u , L , and ν are the Reynolds number, the speed of the fluid flow, the characteristic length of the main channel, and the kinematic viscosity of the fluid, respectively. The characteristic length L is approximated by the cross-sectional dimensions of the main channel by

$$L = \frac{4A}{P} = \frac{2(wh)}{(w+h)}, \quad (2)$$

where A , P , w , and h are the area, the perimeter, the width, and the length of the cross-section of the main channel, respectively. The speed of the fluid flow, u , is calculated as the average speed over the cross-section from the experimentally measured volumetric flow rate. The kinematic viscosity of the fluid is set as $\nu = 0.893 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$.

In Fig. 5(f), the first vortex can be observed when the driving pressure reaches 110 kPa. By approximating the atmospheric pressure being 100 kPa, a pressure drop of 10 kPa is enough for generating the split flow at the turning corner. When the driving pressure is gradually increasing to 120 kPa and 130 kPa, the 2nd and 3rd vortices can be visually observed as shown in the experimental images in Fig. 5(f). Here, we would like to note that at the pressure of 120 kPa, although the 3rd vortex has not yet clearly formed, a portion of the 2nd vortex has already flowed into the circular chamber. For the pressure over 130 kPa, the size of the vortex in the circular chamber gradually increased as well as its rotating speed. According to the results in Fig. 5(f), a pressure drop of 30 kPa is the minimum driving pressure for generating VVG of 3 vortices, and its corresponding Reynolds number is about 200.

B. Pinpoint injection in simulations

Figure 6 shows the simulation results where Figs. 6(a) and 6(b) are the top view and the bird's view of the results with the pressure drop of 100 kPa. Each line indicates the pattern of a streamline at a given location on the cross-section of the flow source. It is surprised to see that only the white streamline can go into the circular chamber in VVG mode although the overall flow seems quite complex. Practically, the only flow that goes into the chamber can be used for injecting contents into the chamber. We called the technique "Pinpoint Injection" which means that the content in the circular chamber is injected from a pinpoint on the whole cross-section of the inlet flow. If this is true in experiments, we can significantly reduce the amount of chemical or drug, while applying VVG in applications.

Another interesting observation is that there are many intersections from the top view in Fig. 6(a) which is not possible in actual situation because the flows would interfere each other. According to the bird's view in Fig. 6(b), it is found that the streamlines are very well-ordered in layers without actual intersections. For example, the blue streamline, which is above the white streamline, is flowed through the bottom of the channel in the first vortex and then is curving up to the top of the channel while exiting the vortex. Such a complex but stable fluid flow is not very common and thus motivates us for a further experimental validation.

FIG. 6. The simulation results of flow patterns. Streamlines from different locations at source are presented in different streamlines in different colors. (a) The top view. (b) The bird's view.

C. Pinpoint injection in experiments

Figure 7 shows the images captured from experiments using the setup shown in Fig. 2(b). It can be clearly seen in Fig. 7(a) that the circular chamber is fully filled with water-bead solution which is from a limited range of streamlines from the inlets. The measured distance from the stream to the channel wall is measured as $33.8\ \mu\text{m}$ and the width of the stream is $37.1\ \mu\text{m}$.

According to the result in Fig. 7(a), we visualized the chamber color turning transparent which is mostly from the focused stream in the main channel, while the amount from the other two inlets is supposed to be very small or even negligible. In Fig. 7(b), the location of the focused stream is slightly moved away from the upper wall and results in a clear change of the pattern in the circular chamber. It is believed that the focused stream in Fig. 7(b) covers only a part of the stream that goes into the circular chamber. When the stream is moved further away from the right wall as shown in Fig. 7(c), the color of the circular chamber is completely changed to blue. It is a clear indication that there is no overlap between the focused stream in Fig. 7(c) and the stream going into the chamber. Figure 7(d) shows that a focused stream is about at the center of the channel, and the color of the chamber remains the same as the one in Fig. 7(c).

Since the tube pinching shown in Fig. 2(b) is only on one side of the inlet, the manipulation of the focused stream is only ranged to a half of the channel. Nevertheless, it is clear that the stream going into the circular chamber in Fig. 7 is limited in certain range, which is very similar to the simulation results shown in Fig. 6. Moreover, the flow patterns are also similar between the experiments and the simulations. For example, the stream located at the center of the channel in the simulations in Fig. 6 is split into two streams where one continuously flow toward the outlet and the other flow through the vortex. Such a pattern can be observed in both

FIG. 7. The experimental results of the flow patterns from different stream positions. Different distances between the stream and the wall, d , and the width of the stream, ws , resulted in different patterns. (a) $(d, ws) = (33.8, 37.1)$ [μm]. (b) $(d, ws) = (47.3, 27.0)$ [μm]. (c) $(d, ws) = (50.6, 20.3)$ [μm]. (d) $(d, ws) = (60.8, 20.3)$ [μm]. Multimedia view: <https://doi.org/10.1063/1.5031082.1>

Figs. 7(c) and 7(d). Therefore, it is fair to state that the simulations and experiments are matching.

In order to further identify the range of the stream that goes into the chamber, we define a “critical stream” as the stream that goes into the circular chamber (i.e., the flow originated from

the pinpoint). Figure 8 shows the analysis results based on the captured images in Figs. 7(a)–7(d). The bars in Fig. 8 represent the location and size of the focused streams in Fig. 7 where the y-axis is the perpendicular distance from the upper channel wall to the stream. Because the chamber in Fig. 7(a) is filled with the water-bead solution and there is no water-bead solution that enters the chamber in Fig. 7(c), the range of critical stream is expected being within the range as the shaded area highlighted in Fig. 8.

D. VVG at different turn angles

Figure 9 shows the effect of turning angle to the vortex size in the chamber. Microfluidic channel with the turning angles of 30° , 60° , 90° , and 120° are fabricated as shown in Fig. 9(a). The driving pressure is controlled by a proportional-integral-derivative (PID) controller, while the water-bead solution is used for vortex observation. Two examples are shown in Figs. 9(a) and 9(b) where the driving pressure is 140 kPa and 160 kPa, respectively. The overall results are summarized in Fig. 9(c) where the y-axis indicates the percentage of the vortex size covering the whole chamber area. The first is that the vortex size is getting bigger with the increase in driving pressure. The other is that the growth of the vortex size is slower when the turning angle is smaller. It provides the information that a sharply turned corner can introduce VVG easier but is not necessary for generating VVG. From the perspective of fluid dynamics, the inertia is more pronouncing at a shaper changing of flow direction, so the results in Fig. 9 are reasonable.

IV. INVERSE MAPPING FOR PINPOINT INJECTION

It is very challenging to observe the location and area of the critical stream from experiments because there is no such an observation device, to the best of the authors' knowledge that can easily monitor the 3D dynamic flow inside a microfluidic channel. Thus, CFD becomes a convenient way, and likely the only way, to further investigate VVG. We can place a trace surface (TS) inside the simulation model and obtain the streamlines through the area in the simulation. That is, we can track the source of the flows inside the chamber and find out the location and the size of the source of the flow, and the tracking of the source is refereed as "Inverse Mapping" here.

Figure 10 shows the inverse mapping from a trace surface in the main channel. All the streamlines caught at the grids on the TS are tracked and the sources of the tracked streamlines on the corresponding surface (CS) are shown as the red points in Fig. 10(b).

Figure 11 shows the inverse mapping of different trace surfaces (TS_i $i = 1, 2, 3$) inside the circular chamber by simulation. Figure 11(a) is the overview of the simulation environment

FIG. 8. The analysis of the locations and widths of the focused stream (white) in Fig. 7. According to the results, the range of the critical stream is estimated as the shadow area in the chart.

FIG. 9. Different driving pressure and turning angles result in different vortices in the chamber. (a) Sample results at the driving pressure of 140 kPa. (b) Sample results at the driving pressure of 160 kPa. (c) The relationship between vortex size and driving pressure.

where three different surfaces, TS1, TS2, and TS3, are set in the chamber for the inverse mapping. All the streamlines passing through the specified TS will be tracked and shown on the CS on the upstream side of the flow. According to Figs. 11(b)–11(d), the tracked streamlines on TS formed a limited area on CS, where the area indicates the region of the previously described “pinpoint.” The pinpoint can be determined in simulations for different VVG designs and can be used for precise drug injection in applications. We would like to note that direct mapping and inverse mapping would show the same results because it is done with numerical simulations. The reason for using inverse mapping instead of direct mapping is that it is much more

FIG. 10. The inverse mapping of a trace surface at the turning corner. (a) The simulation settings. (b) The streamlines pass through the grids on TS and the corresponding sources on CS.

FIG. 11. The inverse mapping of 3 different surfaces inside the chamber. (a) The simulation settings. (b) The inverse mapping from the surface TS1. (c) The inverse mapping from the surface TS2. (d) The inverse mapping from the surface TS3.

efficient, in terms of computing time. With direct mapping, we have to set a very high density of tracking streamlines on the inlet cross-section because the streamlines entering the chamber are from a very limited area, the pinpoint. Direct mapping usually finds only very few streamlines entering the chamber, and most of computing time are for the streamlines not-entering the chamber. On the other hand, the inverse tracking would only track the streamlines entering the chamber, so that it is much more efficient and greatly reduces the computing time.

V. DISCUSSION

A. Multiple colors for confirming the flow patterns

While the experimental results shown in Fig. 7 contain only two kinds of solution, we conducted additional experiments with multiple colors for clearly comparing the flow patterns to

FIG. 12. Multiple colors of the solution are used for confirming the experiments with the simulation results in Fig. 6. Streams (1)–(5) indicate five independent streams from upstream.

the simulation results shown in Fig. 6. Figure 12 shows an experimental result with multiple colors and the results were obtained using a different microfluidic chip with multiple inlets. The streams are labeled with number (1)–(5) for color layers from the top to the bottom.

The top flow (1) of cyan in Fig. 12 was supposed to flow along the channel wall through the turn when the flow speed is low and Reynolds number is below 10. In this case whose speed is sufficient for generating VVG, it suddenly bent before the turn and later showed up on the top of the first vortex, as (1') shown in Fig. 12. The pattern of flow from (1) to (1') is similar to the blue streamline in Fig. 7, but the flow after (1') cannot be clearly visualized. It may be due to the shortened width of flow (1) that makes the color less visible. Flow (2) contains the water-bead solution and it whirled around the corner and entered the circular chamber as the pinpoint injection introduced in Secs. I–IV. Flow (3) also rapidly bent before the turn and then hit the lower channel wall in Fig. 12. The split flows (3') and (3'') from flow (3) were move the left and right, respectively. The flow (3') whirled around the corner and disappeared after hitting the flow (1), while flow (3'') directly went to the right after the splitting point. Flows (4) and (5) were simply passing the turn with a parabolic curve without any vortex flow. The experimental results in Fig. 12 provides a clear one-to-one mapping to the simulation in Fig. 6.

B. Potentials of VVG and pinpoint injection

VVG and the pinpoint injection have great potentials in microfluidic applications, especially in cell-level research in biology. For example, drug test using microfluidic device has been popular recently,³⁰ and VVG can directly control the composition inside a microfluidic chamber for quantitative analysis of drug response. The volume of drug can be significantly reduced if we inject the drug with the proposed pinpoint injection, and it is particularly useful when the drug is rare or expensive.

Moreover, VVG also works like a reduction gear in a microfluidic chip. The vorticity, the flow speed of a vortex, is reduced from the first vortex to the second vortex, while the third vortex is the slowest. The speed of the third vortex can then be controlled in high resolution with such a reduction mechanism and is convenient for on-chip mixing and cell culture. For example, long-term cell culture on a chip usually needs a very careful control of flow in order to refresh the culture medium without washing out cells.³¹ If we culture cells inside the VVG chamber, it becomes easier to control the speed for low-speed medium refreshment.

VI. CONCLUSIONS

An interesting microfluidic vortex flow called VVG is presented and the flow patterns of VVG have been investigated through both experiments and simulations. The flow of VVG is found stable and consistent even though the flow patterns are complex in three dimensions. According to the results, VVG are formed by the flow from a pinpoint on the cross-section of

the inlet, and therefore, the contents of the chamber, where the third vortex is located, can be controlled using the VVG-based pinpoint injection. A technique of inverse mapping is proposed and it helps to locate the position of the pinpoint. The potentials of VVG, such as mixing and drug test on a microfluidic platform, are discussed.

ACKNOWLEDGMENTS

This work was partially supported by JSPS KAKENHI of Japan, Grant No. JP15H05761, JP17K18854 and the Ministry of Science and Technology of Taiwan, Grant No. 107-2218-E-009-027.

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