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Visualization of particle focusing in stirred chaotic flow

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Corresponding Author:	Steven Wang ETH Zürich Zurich, Zurich SWITZERLAND
Corresponding Author Secondary Information:	
Corresponding Author E-Mail:	steven.wangce@gmail.com
Corresponding Author's Institution:	ETH Zürich
Corresponding Author's Secondary Institution:	
First Author:	Steven Wang
First Author Secondary Information:	
Other Authors:	Utku Gulan
	Markus Holzner
	Erich Windhab
	Mo Jiang
Order of Authors Secondary Information:	
Abstract:	In general, there is yet universal agreement to be made on the tendency of finite-sized particle motion in laminar fluid flow. In this study, the behavior of almost neutrally buoyant particles in a laminar chaotic flow system was investigated. We found an unexpected category of particle clustering effect whereby particles can spontaneously localize or cluster into small region(s) of the flow. We used a capsule tracking method to trace out the helical orbits, and this method provides a sound qualitative way to visualize particle trajectories inside the chaotic flow system. Furthermore, we performed three-dimensional particle tracking velocimetry (3D-PTV) to quantify the Lagrangian behaviour of both inertial and passive tracer particles.
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TITLE:
Visualization of particle focusing in stirred chaotic flow

AUTHORS:
Gülan, Utku
Department of Cardiology
University of Zürich
Zürich, Switzerland
and
Institute of Environmental Engineering
ETH Zürich
Zürich, Switzerland
utku.guelan@ifu.baug.ethz.ch

Holzner, Markus
Institute of Environmental Engineering
ETH Zurich
Zurich, Switzerland
holzner@ifu.baug.ethz.ch

Jiang, Mo
Department of Chemical Engineering
Massachusetts Institute of Technology
Boston, MA, USA
mojiang@mit.edu

Windhab, Erich J.
Laboratory of Food Process Engineering
ETH Zürich
Zürich, Switzerland
erich.windhab@hest.ethz.ch

Wang, Steven[1,2]
[1]Laboratory of Food Process Engineering
ETH Zürich
Zürich, Switzerland
[2]Present address: Department of Chemical Engineering and Advanced Materials
Newcastle University
Newcastle, United Kingdom
steven.wang@newcastle.ac.uk

CORRESPONDING AUTHOR:
Steven Wang

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Trapping, particle tracking, flow instability, laminar flow, stirred flow, 3D PTV

SHORT ABSTRACT:
Here, we present a protocol to visualize an unexpected trapping phenomenon of inertial particles in a stirred tank under laminar flow conditions.

LONG ABSTRACT:
In general, there is yet universal agreement to be made on the behavior of finite-sized particle motion in laminar fluid flow. In this study, the behavior of almost neutrally buoyant particles in a laminar chaotic flow system was investigated. We found an unexpected category of particle clustering effect whereby particles can spontaneously localize or cluster into small region(s) of the flow. We used a capsule tracking method to trace out the helical orbits, and this method provides a sound qualitative way to visualize particle trajectories inside the chaotic flow system. Furthermore, we performed three-dimensional particle tracking velocimetry (3D-PTV) to quantify the Lagrangian behavior of both inertial and passive tracer particles.

INTRODUCTION:
The motion of particles is a common phenomenon encountered in nature and engineering. Examples include: fine sediment in the rivers, raindrops formed in the cloud, and tiny crystals produced in the multiphase crystallizer. Particles can behave like infinitesimal fluid elements and strictly follow the underlying carrier-fluid flows. These particles are called passive particles. A passive particle does not alter the surrounding fluid velocity field and instantaneously matches its own velocity to variations in fluid velocity. In laminar flows, the Lagrangian motion of a passive particle at location $\boldsymbol{X}_p = (X, Y, Z)$ moving with respect to fluid velocity field $\boldsymbol{u} = (u, v, w)$ is described by the following kinematic equations:

$$\frac{dX}{dt} = u(X_p, t)$$

$$\frac{dY}{dt} = v(X_p, t)$$

$$\frac{dZ}{dt} = w(X_p, t)$$

(1)

The assumption in obtaining this set of equations is that the particle follows the fluid flow velocities and does not influence $\boldsymbol{u}$. Unlike the turbulent flows, in which the quasi-random changes in space and time of the velocity field is the factor that dominates transport, in laminar flow chaotic advection controls the transport of particles[1].

Inertial particles have non-negligible inertia that makes their trajectories deviate from the ones of passive particles. Inertia can be due to density difference between fluid and particles, or it can originate from finite size of the particle. Inertia due to the finite-sized particles modifies the trajectories of particles with respect to passive tracers[2,3]. The critical parameter describing the particle motion in fluid flow is the particle's Reynolds number:

$$Re_p = \frac{|\boldsymbol{V}_p - \boldsymbol{u}|L}{\nu}$$

(2)

where $\boldsymbol{V}_p$ is the absolute velocity of a rigid spherical particle, $\boldsymbol{u}$ is the velocity of the ambient fluid, L is the characteristic length scale of the flow and ν is the kinematic viscosity. For a passive particle, Re_p=0 as $|\boldsymbol{V}_p - \boldsymbol{u}|$ vanishes; for small-enough inertial particles, Re_p<<1 and it is usually assumed that when particle concentration is low, particle motion does not affect the ambient $\boldsymbol{u}$.

Although agitated stirred vessels have been in consistent use for a number of centuries, much less is known about the trajectories of finite-sized particles inside these vessels. The handling of finite-sized or fine particles in stirred systems is actually a crucial process that occurs throughout the chemical, mineral, pharmaceutical, food, water and biotechnological industries[4]. It should be noted that the versatility of these tanks has made them the most popular mixing equipment for several centuries.

In a stirred system, two fundamental mechanisms are responsible for fluid mixing: diffusion and advection. In practice, diffusion (at the molecular level) alone is not efficient at all for mixing, while chaotic advection is primarily responsible for transport of matter in a flow and it is required for efficient mixing. In particular, chaotic advection/motion is the only way to enhance transport rates for mixing, reaction, and heat and mass transfer for almost all laminar flow applications (industrial, biological, and geotechnical applications). In a laminar mixing system, the impeller provides a periodic perturbation to create a sea of chaotic fluid motion surrounding the vortex tubes, which are called Kolmogorov Arnold Mosur (KAM) tubes in the non-linear dynamical system[1,5]. As the fluid flow does not advect material through the boundaries of such tubes, their presence is a great barrier for efficient mixing. Over the last decades, significant progress has been made on understanding advection of passive particles in these stirred systems. The advection of non-passive/inertial particles in the stirred tanks, on the other hand, remains a largely unexplored area to date.

Three-dimensional particle tracking velocimetry (3D-PTV) is a non-intrusive image-based flow measurement technique which allows three-dimensional access to particle trajectories, flow velocities and velocity derivatives simultaneously[6]. 3D-PTV has been in use for over a few decades as a Lagrangian flow measurement technique[6-9].

In this paper, the motion of inertial particles in fluids will be studied via novel experimental approaches. Particular attention will be given to a stirred flow system, an arrangement used globally in the processing industries. We will expose an unexpected trapping effect: when vortex tubes are present in a laminar flow system, particles do not mix but they get trapped which is counter intuitive to one’s expectation. In the study, in addition to qualitative measurements using LED capsules, we will introduce Lagrangian flow information obtained by the 3D-PTV technique that is particularly well suited to provide detailed statistical information on the motion of inertial particles in a confined region.

PROTOCOL:

1. **Prepare the stirring system to capture the trajectories of large capsules**

1.1. Prepare the stirring system. Use a cylindrical tank, 190 mm in diameter, placed inside a rectangular acrylic aquarium. The schematic of the tank is shown in **Figure 1a**. Fill the outer tank with working fluid, i.e. pure glycerin, to minimize the optical distortion.

1.2. Fill the tank with pure glycerin (>99.9%). The viscosities of glycerin were found to be in the range of 1.10-1.17 Pa, at room temperature 22 ^{o}C.

1.3. Force the flow in the tank using an impeller. Run all the experiments at a particular speed corresponding to a particular Reynolds number (Re ~ 130) to ensure that the system is within the laminar flow regime (rotating speed: 1100 rpm). Place a 7 cm 6-blade Ruston turbine in the center of the cylindrical tank.

[Place Figure 1 here]

1.4. Install the light-emitting diode (LED), battery, 8-bit micro-controller, infrared optical transmitter-receiver into the large transparent capsules that have a diameter of approximately 28 mm[10]. Capsules with LED used in this study are shown in **Figure 2**.

2. **Perform qualitative measurements using LED capsules**

2.1. Place the camera above the liquid level, and adjust the camera aperture to minimize the background effect in the dark environment[10]. The distance between the camera and the liquid level is about 20 cm.

2.2. Switch on the LEDs for several capsules, and then manually release them at the liquid surface. Turn off the light simultaneously when injecting the capsules.

2.3. Take long exposure photographs (exposure time: ~ 30 s) to trace out the colored pathlines[10].

3. **Visualization of trapping of small inertial particles**

3.1. Establish the flow by setting the impeller speed at 1100 rpm (Re = 133), and then pour ~13 g small polystyrene particles (with uniform size and density, a = 1.4 mm, $\rho_p / \rho_f \sim 0.80$) into the stirred vessel. Turn on the light and face the camera towards the liquid from the side. Use a standard aperture.

3.2. Place the camera towards the region of interest (ROI) that covers the entire stirred tank.

3.3. Take sequential images from the front and then analyze the particle distribution as a function of time. Take four images at t ~0 min, 1 min, 3 min, 5 min, and 30 min respectively.

3.4. Use ImageJ to obtain the pixel value distribution, which is assumed to be linearly proportional to the particle number distribution. Assume that more particles cause larger pixel numbers in any particular area[5].

4. **Prepare setup for 3D particle tracking**

4.1. Prepare the illumination of the ROI which covers the entire stirred tank. Use a diode-pumped Nd-YLF laser (527 nm) as a light source. The average power is 100 W at 3 kHz. Widen the laser beam to a volume that covers the ROI using a beam expander and a cylindrical lens[6].

4.2. Place the camera towards the ROI and adjust the alignment of the image splitter and the mirrors. Arrange the mirrors such that the acquired images for all four mirrors cover the same domain at an angle of around 45° and at comparable distances such that all four views are within the focused distance set by the lens[6].

4.3. Use a high speed camera, with a full resolution of 1024x1024 pixels and 7000 fps, to acquire images with high temporal resolution. Use a 60 mm f/2.8 D lens to visualize the flow. Adjust the frame rate.

4.4. Adjust the seeding density of the tracer particles for both single particle and flow velocity measurements.

4.4.1. For the single particle tracking, use a wooden particle with a diameter of 2 mm.

4.4.2. For the flow velocity measurements, use ~1000 fluorescent rhodamine particles with a diameter of 200 µm as tracer particles.

4.5. Calibrate the extrinsic and intrinsic camera parameters using a static calibration target.

Note: The calibration target comprises a number of points with precisely known coordinates. For higher measurement accuracy in camera direction, the calibration target is layered on different planes[6]. The position accuracy of the detected particles is estimated to be ~ 9 microns in image space and 0.35 mm in 3D physical space.

5. **Processing of the PTV data in Matlab**

5.1. Write a Matlab program to detect the particles in each frame after high pass filtering the recorded images[6].

5.2. Find the corresponding particles in the three images of the particles detected in one image and intersect the epipolar lines of corresponding particles to assess the position of them in three-dimensional space.

5.3. Track the particles in each frame and obtain Lagrangian trajectories.

REPRESENTATIVE RESULTS:

Temporal evolution of small particle distribution shows that particles initially follow the fluid flows at the liquid surface and then were dragged into the liquid. At that instant, a novel trapping effect is initiated which drags the particles into the system. Particles dragged remain in the vortex tube once they are trapped in the system. The tracking results confirm that inertial particles can deviate from the fluid streamlines and subsequently move into a vortex tube in a laminar flow tank (**Figure 3**).

[Place Figure 3 here]

As shown in **Figure 3**, the small inertial particles (~ 1 mm) tend to migrate into two bands as time progresses. After 30 min, almost all the particles move into two specific regions of the tank, whilst the remaining regions become clarified. This striking behavior has been explained from perspectives of dynamical systems: a coexistence of repelling and attracting vortex tubes in a laminar chaotic flow is mainly responsible for this effect[5, 10]. One innovation here is that we can visualize the trajectories of large inertial particles using modified LED capsules and the result is shown in **Figure 4**. This figure shows that after swirling around chaotically in the viscous liquid, capsules move into the isolated, donut shaped tubes that are present above and below the impeller. Once captured, capsules follow helical paths as passive particles do.

[Place Figure 4 here]

The Lagrangian trajectory of a single particle obtained by 3D-PTV is depicted in **Figure 5**. The recording has been started just after introducing the particle into the system. The black dot represents the three-dimensional position of the particle at t=0. As it is seen from the figure, the particle follows a helical pattern near the propeller until it reaches the vortex tube (**Figures 5a, 5c**). Once it has reached the core of the vortex tube, the particle is forced to move along near the center line of it (**Figure 5b**). The particle residence time near the core of the vortex tube is around 0.32 s. Along the donut shaped tube, the particle follows a helical path (**Figures 5d, 5e**).

[Place Figure 5 here]

The instantaneous velocity magnitude of a single particle along the ROI is shown in **Figures 6a** and **6b**. A high speed region is present near the impeller which ejects the particle away from the impeller. The velocity magnitudes of the particle moving along the donut shaped vortex tube are relatively slow compared to the impeller region.

[Place Figure 6 here]

Finally, the streak visualization of the flow and the time-averaged flow field is shown in **Figure 7**. The streak visualization was obtained by summing 100 consecutive frames. The high speed region and the four vortex regions can be clearly seen from the figure (**Figure 7a**). Velocity magnitude contours with the in-plane components overlayed as vectors at mid-plane is depicted in **Figure 7b**. Impeller region ejects the flow away from the center of the ROI and distinguish it from the two vortices whose cross sections are clearly visible in **Figures 7a** and **7b.**

[Place Figure 7 here]

Figure 1: Tracking setup for particle tracking in a stirred vessel.
(a) Experimental setup consisted of a camera, four image splitters and a stirred tank equipped with a 6-blade turbine; (b) 3D PTV tracking camera was used for tracking the motions of inertial particles; and (c) A 19 cm cylindrical tank was used and the diameter of impeller is 70 mm.

Figure 2: LED capsules (~27 mm) used in the visualization experiments
The spherical capsules (~27 mm in diameter) are able to be inserted into a fluid flow where they become mobilized and able to follow the flow streamlines. Each capsule contains a colored (red, green, blue, or yellow) light-emitting diode (LED), battery, 8-bit microcontroller, infra-red optical transmitter-receiver and other transducers[10].

Figure 3: Time evolution of polystyrene particle (~1.4 mm, $\rho_p = 0.80$) distribution in a 3D chaotic system.
Flow is established at a particular speed, corresponding to a particular Reynolds number (Re ~ 130) to ensure that it is within the laminar regime, and then particles (with uniform size and density) are poured into the mixing vessel. The particles initially follow the fluid flows at the liquid surface and then were dragged into the liquid. In this sequence, a novel trapping effect is triggered when particles are dragged into the system. Localization starts almost immediately, after a few minutes more particles have moved into the rings. Particles remain in the ring – in this case occupying about 10% of the total fluid volume for as long as *Re* is held constant. The right-most image is 30 min after introduction of the particles[5].

Figure 4: Path lines of large capsules moving inside the vortex tube, exposure time: 30 s
The LEDs were switched for several capsules and then manually inserted into the stirred system. Photographs were taken, using long exposure times (~ 30 s), which allows the tracing of the colored path lines essentially owing to the motion of the capsules in the stirred system. Different path lines can be distinguished by using different colors[5].

Figure 5: Lagrangian trajectories of a single particle for a time interval of 7 s from side views (a,c), top view (b) and 3d view (d,e) (The black marker represents the starting point of the motion)
The single particle motion was recorded with 1000 frame per second for a time interval of 7 s. The particle was introduced to the system at the beginning of the recording. Lagrangian trajectories depict the helical motion along the orbit of the vortex tube which agrees with the LED measurement.

Figure 6: Time evolution of velocity magnitude along the Lagrangian trajectory of a single particle for a time interval of 7 s from side (a) and top (b) views.
Lagrangian trajectories are color-coded with the velocity magnitude to provide both qualitative and quantitative information on the flow. The time evolution of the Lagrangian trajectory shows that the particle introduced from the top of the tank moves it reaches to the impeller where it forces to eject the particle away (**Figure 6a**), thereafter the particle is trapped into the donut shaped vortex tube (**Figure 6b**).

Figure 7: Streak visualization of the flow (a) and velocity magnitude contours with the in-plane components overlayed as vectors at mid-plane (b)
The streak visualization was obtained by summing 100 consecutive frames which is temporally high enough to visualize the high speed region and four recirculation zones (Figure 7a). The velocity magnitude contours show that the higher velocity region develop in the vicinity of the impeller whereas the velocity is lower in the recirculation regions (Figure 7b).

DISCUSSION:

The tracking results reported in this study confirm that large inertial particles can deviate from the fluid streamlines and subsequently move into a vortex tube in a laminar flow tank. Given that this sort of stirred vessel has been widely used for a number of applications, examples of which range from benchtop beakers to large industrial vessels, it is highly desirable to perform qualitative and quantitative measurements in order to understand the underlying mechanism. Future approaches will be taken to map out the spatial extent of repelling regions, where inertial particles can scatter from their underlying fluid flows. On the other hand, the fundamental understanding on the impact of inertia on particle trajectories in the 3D chaotic flow will be obtained through the 3D PTV measurements.

We also realize that this clustering phenomenon provides a sound basis for effective solid-liquid-separation technologies. In a preliminary demonstration, almost 80% purified liquid can be obtained by simply using a stirred tank[5]. To achieve a more effective solid-liquid separation, we will need to pay particular attention to dependencies of the clustering rate, which is directly linked to the effectiveness of the separation method. Obviously, the spatial and temporal distribution of repelling and attracting regions are the most important factors in influencing the clustering rate of particles. We expect that quantitative measurements are necessary to understand the relationship between the clustering rate and the spatial/temporal distribution of repelling regions.

In this study, the streamline flow visualization functionality of the capsules was used. The installation of the circuit board, the LED and the battery in a single capsule makes it a practical challenge that has to be simplified/optimized. This technique can be used for qualitative measurements for motion of *large* inertial particles. At present, we are developing a more sophisticated method and algorithm to obtain particle-velocity fields and quantify their path lines inside the flow systems. Similar to 3D-PTV, the tracking algorithm can also be used to reconstruct particle orbits from the experiments and plot the particle locations on x, y, z axes separately. In addition, the installation of sensors could be also used to measure the pressure and the temperature along the particle pathline[11]. The multifunctionality of capsules can make it an ideal candidate for many simultaneous measurements in large-scale flow systems.

As mentioned above, LED capsules provided qualitative results on the streamline flow. On the other hand, 3D-PTV was used for both qualitative and quantitative information about the flow. Given that the single particle tracking obtained by 3D-PTV depicts a considerable variation of the magnitude of the instantaneous velocity along the trajectory, instantaneous acceleration and hydrodynamic stresses along the trajectory will be of interest in the future studies. The only limitation of the technique at high Re numbers is that the recording time is too limited to capture the entire time evolution of the trapping phenomenon which requires around 30 minutes recording time. We recorded at 1000 Hz to capture fast displacement of the particle and the physical memory of the high speed camera is limited to 16 GB corresponding to 0.2 min. Nevertheless, 3D-PTV is a reliable tool to assess the Lagrangian information on the flow field and will be utilized to investigate the effect of inertia in future studies. This imaging tool can be used for a wide variety of phenomena involving particles and slurry, such as crystallization and emulsion. Further, the application can be extended beyond a traditional stirred tank/reactor, but a “stirred” droplet at a much smaller scale with similar physics of mixing and need for particle tracking, such as a millimeter-sized slurry droplet in a tube where crystals grow while flowing and rotating[12].

The capsule tracking method could be used to provide useful qualitative information on where do inertial particles go in fluid flow. The significant drawback associated with the capsule tracking method is that they could alter the surrounding fluid flows. A future direction is to use 3D printing technology to minimize the capsule size[10]. The 3D-PTV method is good for giving quantitative data; however, the authors realize that a larger scale measurement is still presenting a challenge.

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DISCLOURES:
The authors declare that they have no competing financial interests.

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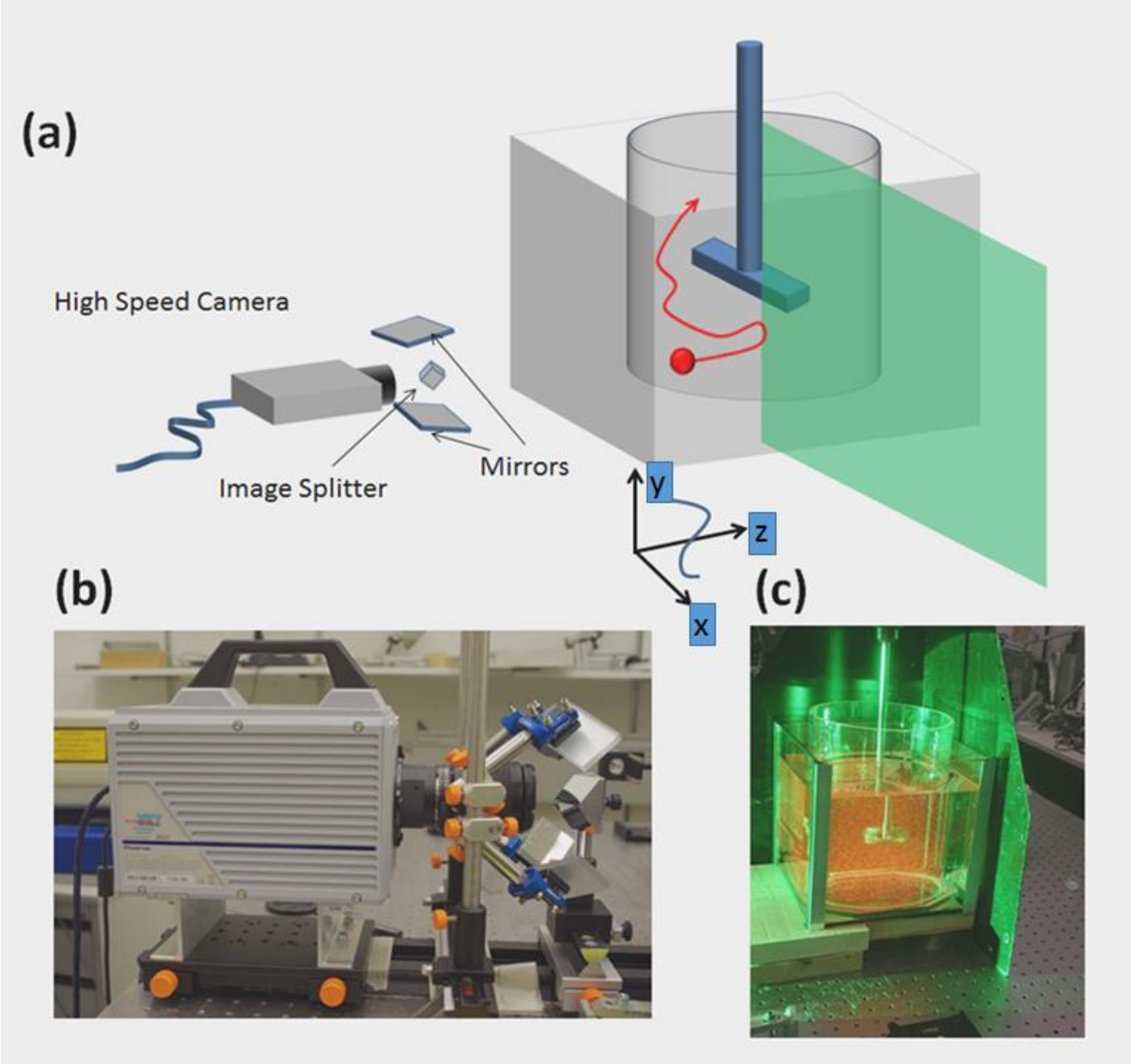
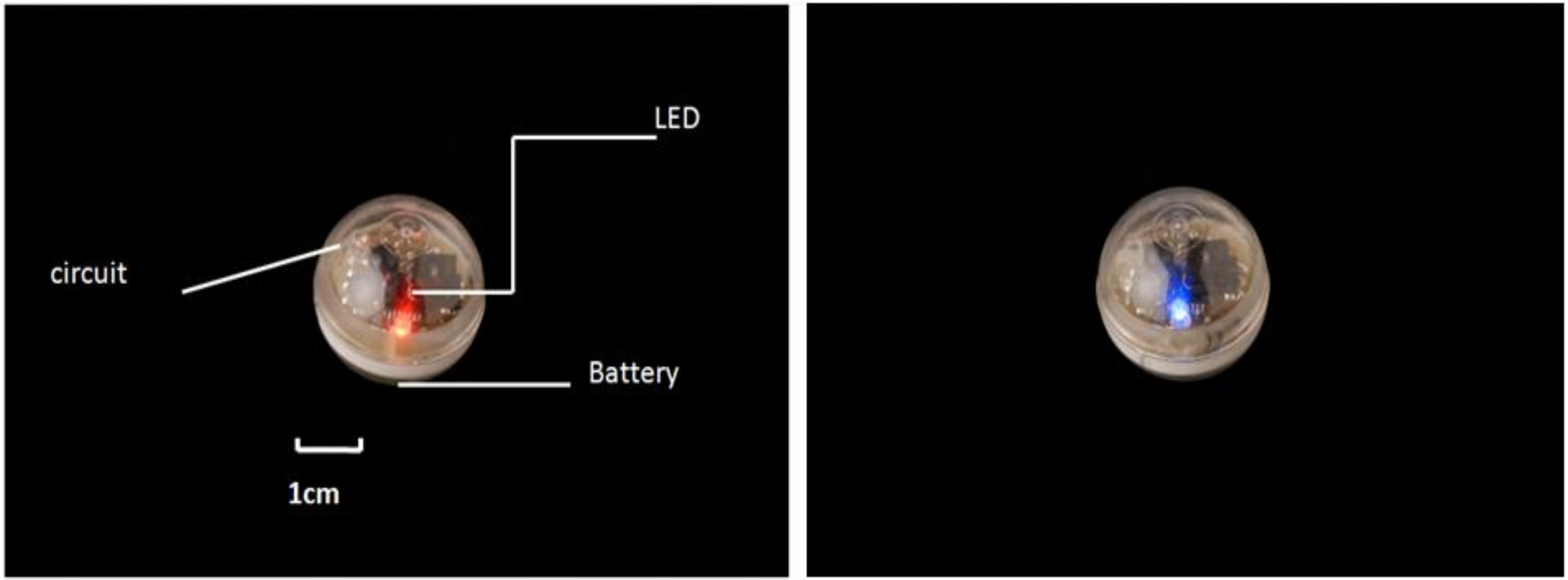


Figure 1



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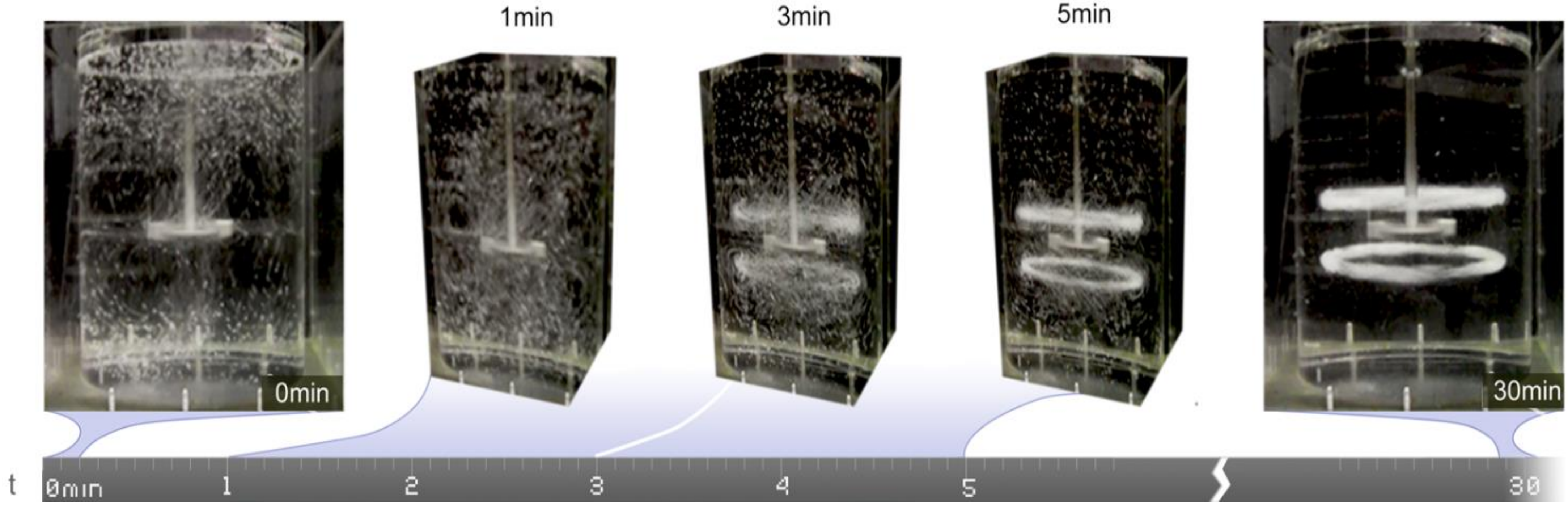

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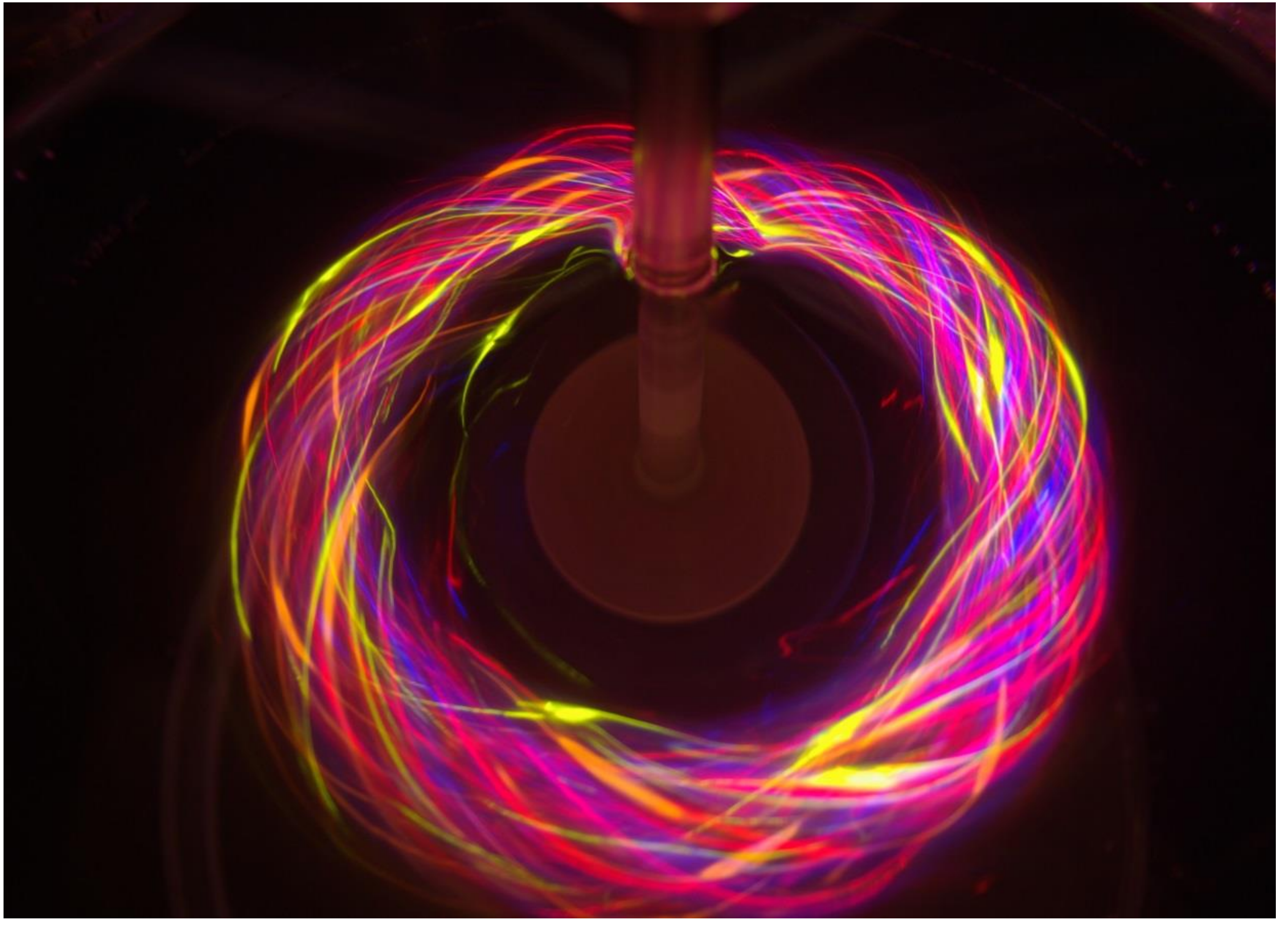

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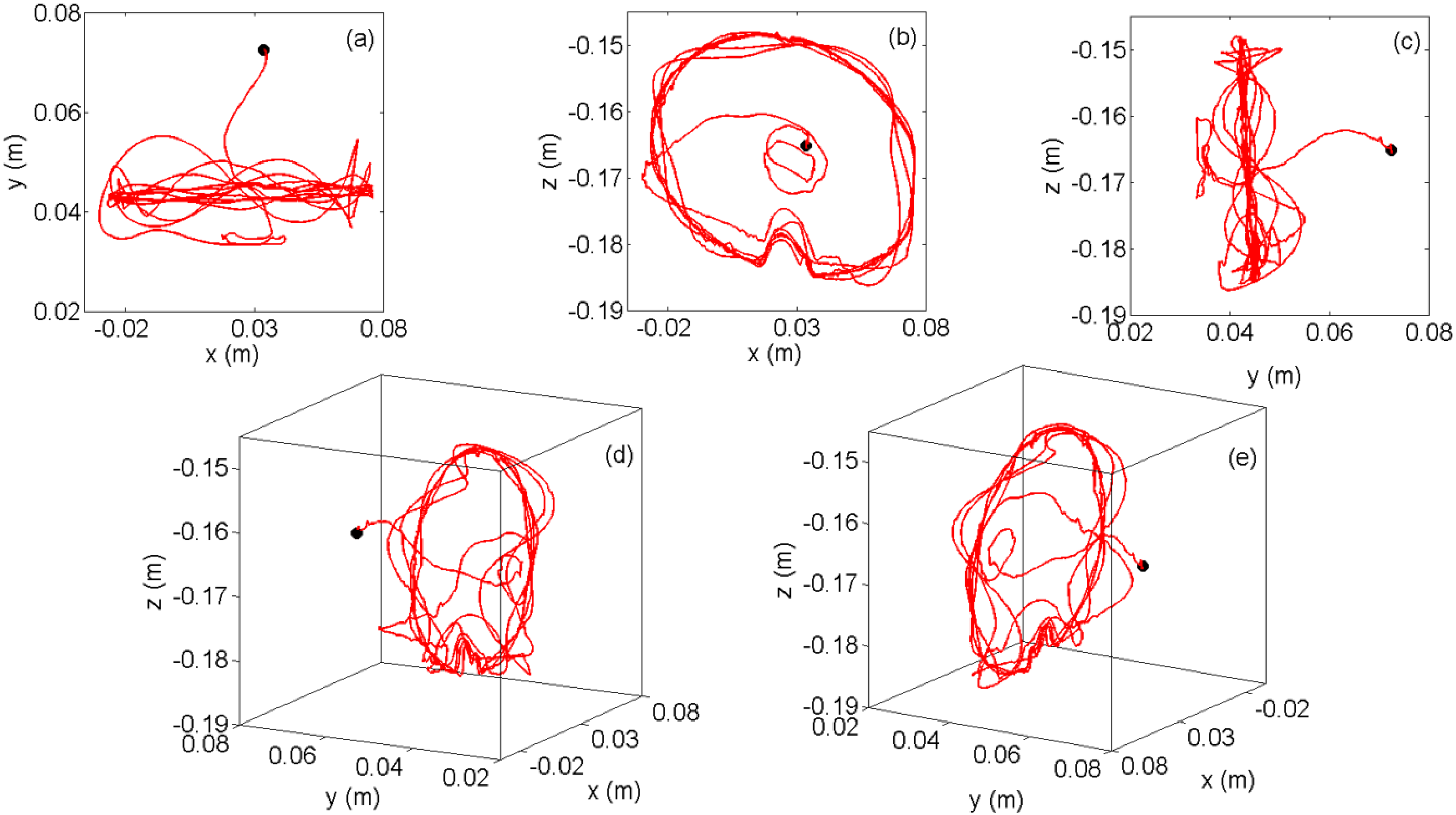
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Figure 5

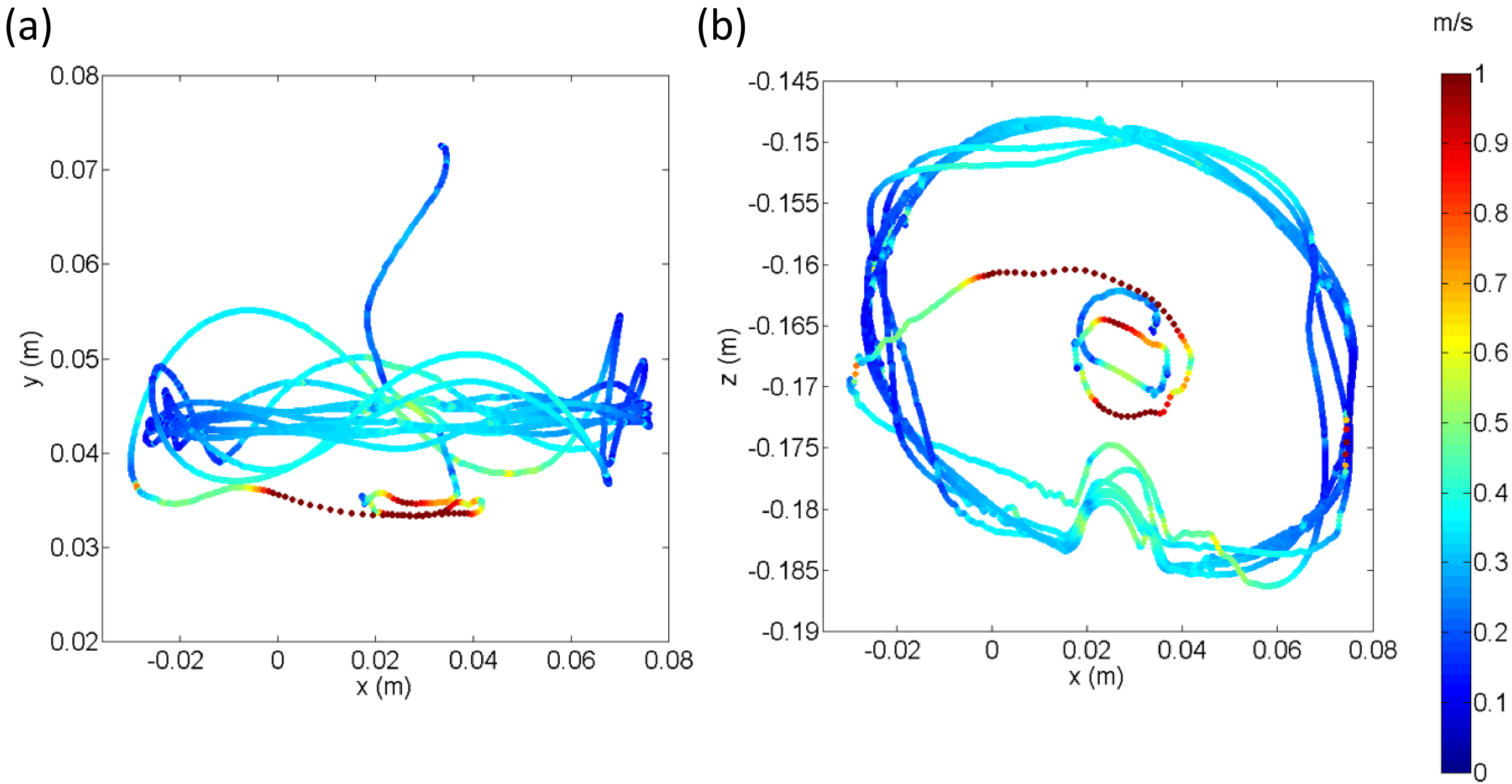
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Figure 6

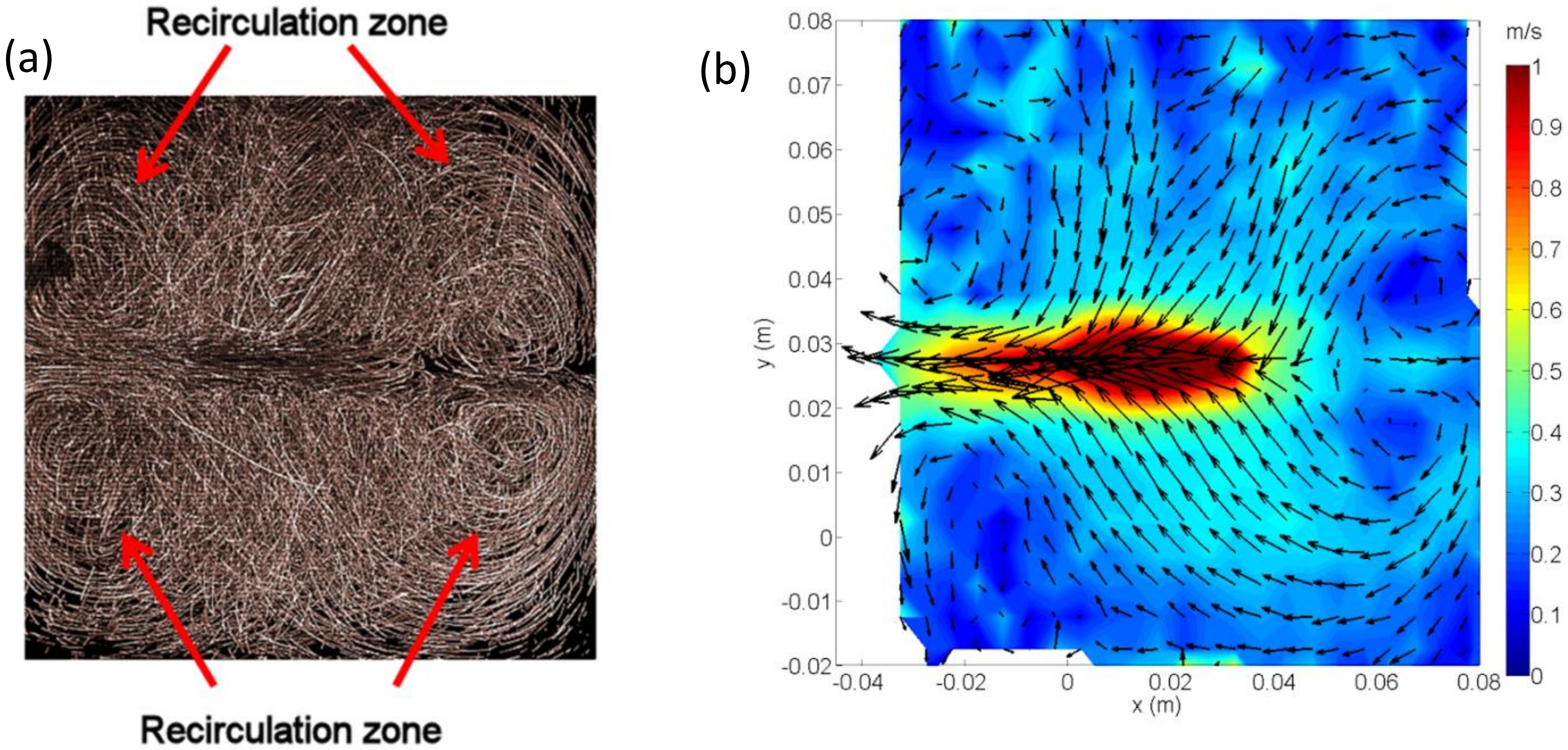
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Figure 7

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
polysyrene particles	N/A	N/A	size: 1mm, denstiy: 1040kg/m3
wooden particles	N/A	N/A	size: 10mm, denstiy: 745kg/m3
seeding particles	N/A	N/A	size: 9 micron
glycerin	N/A	N/A	visocity: 1.17Pa.s, density: 1259kg/cm3
Capsule	N/A	N/A	size: 28mm
Rushton Turbine	N/A	N/A	diameter: 7cm
Overhead stirrer	Heldolph	N/A	high torqure, high precision
Mixing tank	N/A	N/A	diameter: 19cm
Laser	Quanronix, Darwin 527nm	N/A	Diode-pumped Nd-YLF laser
High speed camera	Photron SA5	N/A	1024x1024 pixels and 7000fps
Len	Nikon	N/A	AF Micro Nikkor 60nm f/2.8D

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Title of Article: Visualization of particle focusing in chaotic flow

Author(s): Ethan Galan, Markus Holzner, Mo Jiang, Erich Windhab, Stavros ...

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CORRESPONDING AUTHOR:

Name: Steven WANG
Department: Laboratory of Food Process Engineering
Institution: ETH
Article Title: Visualization of Particle Focusing in Chaotic Flow
Signature: SW. Date: 20.05.2016

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Editorial comments:

The manuscript has been modified by the Science Editor to comply with the JoVE formatting standard. Please maintain the current formatting throughout the manuscript. The updated manuscript (55032_R1_070516.docx) is located in your Editorial Manager account. In the revised PDF submission, there is a hyperlink for downloading the .docx file. Please download the .docx file and use this updated version for any future revisions.

1. Formatting:

-Please use - rather than ~ to indicate a range (see 1.2).

-1.4 – Figure 2 does not seem to be the right figure to cite here.

2. Grammar:

-Line 47 – "in laminar stirred tank"

-1.3 – "condition"

-2.3 – "to linearly proportionally"

-4.4 – "parameter"

-Line 294 – "to large industrial vessel"

3. Additional detail is required:

-1.1 – What is the working fluid?

-1.3 – How does one operate under laminar flow? Is this in a hood? Does the particular speed refer to the speed of the impeller? What speed is used here?

-2.1 – How is the tank run at this speed (what part is set to 1100 rpm)?

-2.2 – How is the camera oriented toward the tank (placement/distance, etc.)?

-3.1 – Is the aperture typically opened or closed for this? What should one see when background is minimized? Are the lights turned off for this adjustment? Does the camera face the top of the liquid or the liquid from the side? This is unclear.

-4.1 – How is the site of the ROI determined?

-4.2 – How/where is the camera positioned?

-4.3 – How many particles are used?

-4.4 – How is calibration performed? What static target is used?

4. Branding:

-1.1 – Perspex

-Figure 1 - Rushton

5. Results:

-Please discuss Figure 2 in the results section.

-Figures 6 & 7 – Please explicitly describe each panel in the figure legends.

6. Discussion: Please discuss the significance with respect to alternative methods (and include independent citations) as well as the critical steps of the method.

Response: All the editorial comments have been carefully addressed. All the typos have been fixed and the additional information have been given in the protocol. Additional discussion has been given in the discussion part to provide the comments on alternative methods.

Reviewers' comments:

Reviewer #1:

General response: We note that Referee 1 remarked that the paper "presents an interesting method for particle tracking and visualization in stirred tank system" and the technique presented will be " very useful to validate computational models in the laminar and turbulent flow regimes". We thank the referee for the useful comments and answer them in the following point by point.

Major Concerns:

There are various information missing from the paper. Here some suggestions:

1. The position of impeller in the tank was not supplied. The aspect ratios affect the mixing process and flow regime. Moreover, the size of tank is smaller than impeller? (refer to table)

Response: The impeller was placed in the centre of the tank. The impeller size is 7cm in diameter, and the tank dimeter is 19cm. All the information have been given and/or corrected.

2. What is the type of impeller?

Response: It is a 6-blade Rushton impeller. Information has been given in section 1.3 in the manuscript.

3. Compare results to studies performed in the literature to confirm data.

Response: We thank the reviewer for giving the valuable comments. Our next paper will provide more quantitative data, thus will allow us to compare results to available date in the literature.

4. In the protocol section: the discussion does not match the order presentation i.e. Figure 2 and 3 are in the wrong order.

Response: We agree with the reviewer that the story line and the figures do not match. We reordered the figures. We believe that the text is more clear.

5. Protocol 2.2: it says 20 mins but Figure shows 30 min as the final time.

Response: We thank the reviewer. The typo is corrected.

6. The coordinate system, (x,y,z) presented in Figure 1 does not match the figures presented in Figure 5.

Response: We agree with the reviewer that the coordinate system in Figure 1 is not identical to Figure 5. Figure 1 is replotted and the coordinate system is corrected now.

7. Figure 5(d) and (e) have not been discussed in the report - consider removing them?

Response: Figure 5d and 5e provides three-dimensional information on the flow. Hence, we believe that it is informative to show both figures. The text in the results section is rephrased to highlight the outcome form both figures.

8. Figure 7 - there is no comparison of flow patterns to results from literature

Response: We thank the reviewer for giving the valuable comments. Our next paper will provide more quantitative data, thus will allow us to compare results to available date in the literature.

Reviewer #2:

Manuscript Summary:

General response: We note that Referee 2 remarked that the paper "would make an in interesting video presentation" and defined that "the instrumentation is well described" and the paper is suitable for JOVE. We thank the referee for the useful comments and answer them in the following point by point.

Major Concerns:

1. Is the software open source?

I think this paper will be useful provided that software for calibration and analysis of particle position is available, and its use explained in the video. Is some sample data and software going to be made available? I think that a reference to an open-source repository with this material would be very valuable.

Response: We thank the reviewer for the comment. As it is outlined in the manuscript, 3D-PTV is not a new technique, but a rather mature one and in this sense it has been validated over the last 20 years or so. The software is open source. What is completely new however, is its application in this novel trapping phenomenon.

2. Briefly mention sources of error in position estimation.

How does motion blur of the particle images due to movement during the camera exposure time (or laser pulse duration) affect the precision of position estimation? If the laser pulse is ~10 ns, then this effect may be negligible, however in reference [6] which this paper seems to build upon, a 25 W continuous wave laser was reportedly used. In which case there may be significant blur during the camera exposure time (say, 1 m/s * 0.1 ms = 100 microns). Is this an important source of uncertainty?

Savin and Doyle (doi: 10.1529/biophysj.104.042457, Biophysical Journal 2005) have a good paper on position estimation (using 2D image data), and their "dynamic error" corresponds to motion blur. I wonder if this is a significant source of uncertainty in this work? Is this what leads to the 350 micron error in "3D space" position estimation?

If not, then what are the sources of error in position estimation for the particles? Does error arise more from the alignment of the imaging system (view splitter and camera)?

Response: We thank the reviewer for the comment. The determination of the particle position from image to object space and the linking those positions in time, forms the main framework of 3D-PTV. On an image, an observed object occupies a patch consisting of a certain number of pixels. Therefore, the particle detection mainly relies on pixel width and grey scale intensity. The center of gravity of the particle is computed as the arithmetic mean of the pixel coordinates weighted by the associated grey values. This particle detection and determination of particle coordinates constitutes the first step of the PTV algorithm. Through a stereoscopic principle and careful calibration of camera positions and orientations, 3D particle positions are computed from 2D images of the particles observed from different viewing directions at a given time instant (Saha, Experimental Analysis of Aggregate Breakup in Flows Observed by Three Dimensional Particle Tracking Velocimetry, ETH Zurich, 2013).

Calibration, i.e. the determination of external and internal camera parameters, such as position, orientation, focal distance, optical axis correction, plays a significant role in obtaining an accurate result. To constitute the correspondences between images, it is crucial to obtain the particle position in real space with high precision. The calibration can be performed either statically or dynamically. The static calibration target comprises a number of points with exactly known coordinates. To acquire a robust calibration along the camera direction, the static calibration target is layered in different planes. The accuracy of the measurement is highly influenced by the calibration. The accuracy of the measurements in 2D is different from 3D as one expects to have relatively higher errors in camera direction compared to the other dimensions. In other words, velocities along the camera direction (z axis) are more difficult to measure due to the limited depth of field. Furthermore, optical aberrations, diffraction, lens distortion, inhomogeneous glass walls disturbing the incidence angle, local temperature gradients affecting the refractive index are the major causes that may reduce the image quality which potentially leads to the large errors in particle coordinate estimation.

3. Cartesian axis labels need to be checked (see Minor concerns - Figure captions).

Response: We agree with the reviewer that axis labels need to be rephrased. All figures are rechecked and now the axis labels are correct.

Minor Concerns:

The quality of the writing seems generally good, but I have a number of specific comments as follows.

Specific comments

Line 50. "tendency of" might mean "behavior of"

Line 64. "match" should be "matches"

Line 88. For equation 2, it should probably be stated that ₩nu is the kinematic viscosity (and not dynamic viscosity), since the other terms are defined.

Line 107. "advent" might mean "advect"

Line 122. "experience" might mean "expectation".
Line 145. The reference should be to Figure 3 (in order of figures in my review copy.)
Line 156. "attain" should probably be "obtain"
Line 156. "pixel number distribution" is more usually written as "pixel value distribution" or "grey level histogram" in my experience.
Line 172. What is the pulse duration of the laser (and its mean power or pulse energy)?
Line 187. What does "image space" and "3D space" refer to exactly? Will the calibration be done using software based on reference [6]? If so, additional explanation will be needed (presumably this will be in the video).
Line 201. The reference to Figure 3 should be Figure 2 (in my review copy) - switch around Figures 2 and 3 in the Figure list.
Line 246. "turbin" should probably be "turbine"

Line 329. "limited" should be "too limited"

Response: We thank the reviewer and all the suggestions were implemented into the text.

Line 303. The particle separation is presumably only effective for particles of some particular size range. Is there space to discuss this?

Response: We thank the reviewer for the valuable comment. We agree that size effect is of interest of our research but for this study it is not in our scope. We will face our research to this direction in our future studies.

Caption
Figure 1a. The Cartesian axes seem to be in a non-standard left-handed arrangement. This is inconsistent with Figure 5 which seems to use a standard right-handed arrangement. Please check the axis labels thoroughly. Please use a right-handed set of Cartesian axes if possible.
Caption
Figure 7b. Is the velocity map really for the XY plane (using the axes in Figure 1a), or is it the YZ plane (in the notation of Figure 1a)? Please check.

Response: We agree with the reviewer that the coordinate system in Figure 1 is not identical to Figure 5 and Figure 7. Figure 1 is replotted and the coordinate system is corrected now.

Additional Comments to Authors:
N/A

Reviewer #3:

Manuscript Summary:

General response: We thank the referee for the useful comments and answer them in the following point by point.

The manuscript presents a method to study the movement of neutral density or lighter particles in a viscous Newtonian liquid. The manuscript presents actually three experimental techniques. First one involves a direct flow visualization which shows how particles introduced at the liquid surface during mixing are trapped in vortex rings created above and below the impeller blades. The second technique involves the introduction of LED capsules at the liquid surface at the beginning of mixing and track their trajectories using a high-speed camera placed above the liquid surface. This technique shows the presence of vortex rings above and below the impeller and the pathways traced by the capsules once they are trapped within the vortex rings thereby confirming the particle-trapping mechanism observed in the first technique. The third method employs a 3D PDV instrument to study the Lagrangian trajectories of particles under laser illumination. This technique provides not only the trajectories of particles but also the relative velocity vectors of the underlying liquid flow. Authors suggest that the phenomenon of particle clustering in the vortex ring can be used for solid-liquid separation in a high viscous liquid.

Major Concerns:

The title of the manuscript 'Visualization of particle focusing in chaotic flow' does not describe the method clearly. Especially the phrase 'focusing in chaotic flow' is not ambiguous,and needs to be rephrased. The solids used in this work are lighter than the liquid phase. Can the clustering technique be used for particles denser than the liquid phase? Can this technique be used in a continuous system where the feed is a slurry and the products are clear liquid and solid phases?

Response: We thank the valuable comment given by the reviewer. As in laminar flow tank, it has been quite well known that the flow is chaotic. We thus change our title to 'Visualization of particle focusing in stirred chaotic flow. 'We agree that particle-liquid separation is of interest of our research but for this study it is not in our scope. We will face our research to this direction in our future studies. However, we have had direct experimental evidence that heavy particles can be made to concentrate into the vortex tubes. This is very surprising, and we are doing more work with the colleagues from the states.

Minor Concerns:

Page,

Line no. Comments/Corrections

59 The motion of particles is a common phenomenon encountered in nature and engineering. - Needs to specify the medium in which the motion of particles is common and important.

Response: We have added ' Examples include: fine sediment in water flow in the rivers, raindrops formed in the cloud, and tiny crystals produced in the multiphase crystallizer.'

86 'where Vp is the velocity of a rigid spherical particle' - What velocity you are talking about? Is it the settling velocity or horizontal velocity of the particle?

Response: Vp is particle velocity relative to the surrounding fluids.

Fig 5 It will be useful if you could elaborate the caption by stating which is the side view, top view and front view.

Fig 6 Same as above

Response: We have given more details in the captions.

145 Capsules with LED are shown in Figure 3 in the manuscript, not in Figure 2. Needs to change figures. What is the density of LED as compared to glycerine?

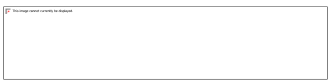
Response: we have modified the captions and orders. The density ratio is 0.71, and it has been stated in the manuscript.

150-151 Why did you choose 1100 rpm in this run? What is the Reynolds number? Is the flow laminar under this condition? What type of 'small' particles were used in this run?

Response: The working liquid glycerine has very high viscosity, and 1100rpm was chosen to maintain a laminar flow, with Re ~ 100. The particles are polystyrene, with diameter of 1.4 +/- 0.4 mm.

222 How was the particle residence time near the core of vortex ring was measured?

Response: Particle residence time corresponds to the time needed for a tracer particle to leave the region of interest. It can be calculated as;



In our analysis, we define the region of interest as the region in the core of the vortex ring.

91 Change 'Whereas' to 'Although'.

106 Change 'advent' to 'advect'

154 'Take four images at t ~0 min, 1 min, 3 min, 5 min, and 20 min respectively'. The last sampling interval in the figure 3 is shown as 30 min, not 20 min. Which one is correct?

156 Change 'attain' to 'obtain'.

161 Change 'Place the camera on the top of the liquid level' to 'Place the camera above the liquid level'.

205 Change 'repeller' to 'repelling'.

219 Change 'until it reaches to the vortex' to 'until it reaches the vortex'.

236-237 Change '(Figure 7, left)' to '(Figure 7a)'.

239-240 'the ROI and distinguish it from the two vortices whose cross sections are clearly visible in Figure 7.' - State in which of the Figure 7 (a or b)?

246 Change 'turbin' to 'turbine'

252 Change 'Reynolds speed' to 'Reynolds Number'

299 Change 'attained' to 'obtained'

257 Is 'rolls' the correct the word to represent the vortex tube ? Can't you use 'rings' instead?

Response: We thank the reviewer. We have seriously considered the comments given by the reviewer, and have made all the necessary changes in the manuscript.