**TITLE:**

Visualization of particle focusing in stirred chaotic flow

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**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 moving with respect to fluid velocity field is described by the following kinematic equations:

(1)

The assumption in obtaining this set of equations is that the particle follows the fluid flow velocities and does not influence ***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 particles1.

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 tracers2,3. The critical parameter describing the particle motion in fluid flow is the particle’s Reynolds number:

(2)

where ***V****p* is the absolute velocity of a rigid spherical particle, ***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, =0 as vanishes; for small-enough inertial particles, <<1 and it is usually assumed that when particle concentration is low, particle motion does not affect the ambient .

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 industries4. 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 system1,5. 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 simultaneously6. 3D-PTV has been in use for over a few decades as a Lagrangian flow measurement technique6-9.

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. 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.
   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 oC.
   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. 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 mm10. Capsules with LED used in this study are shown in **Figure 2**.

1. **Perform qualitative measurements using LED capsules** 
   1. Place the camera above the liquid level, and adjust the camera aperture to minimize the background effect in the dark environment10. The distance between the camera and the liquid level is about 20 cm.
   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.
   3. Take long exposure photographs (exposure time: ~ 30 s) to trace out the colored pathlines10.
2. **Visualization of trapping of small inertial particles**
   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, ρp/ ρf~0.80) into the stirred vessel. Turn on the light and face the camera towards the liquid from the side. Use a standard aperture.
   2. Place the camera towards the region of interest (ROI) that covers the entire stirred tank.
   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.
   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 area5.
3. **Prepare setup for 3D particle tracking** 
   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 lens6.
   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 lens6.
   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. Adjust the seeding density of the tracer particles for both single particle and flow velocity measurements.
      1. For the single particle tracking, use a wooden particle with a diameter of 2 mm.
      2. For the flow velocity measurements, use ~1000 fluorescent rhodamine particles with a diameter of 200 µm as tracer particles.
   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 planes6. The position accuracy of the detected particles is estimated to be ~ 9 microns in image space and 0.35 mm in 3D physical space.

1. **Processing of the PTV data in Matlab**
   1. Write a Matlab program to detect the particles in each frame after high pass filtering the recorded images6.
   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.
   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 effect5, 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.**

1. 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 transducers10.

**Figure 3: Time evolution of polystyrene particle (~1.4 mm, ) 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 particles5.

**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 colors5.

**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 tank5. 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 pathline11. 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 rotating12.

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 size10. 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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