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A synchronized particle image velocimetry and infrared thermography technique applied to an acoustic streaming flow

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Abstract

Subsurface coherent structures and surface temperatures are investigated using simultaneous measurements of particle image velocimetry (PIV) and infrared (IR) thermography. Results for coherent structures from acoustic streaming and associated heating transfer in a rectangular tank with an acoustic horn mounted horizontally at the sidewall are presented. An observed vortex pair develops and propagates in the direction along the centerline of the horn. From the PIV velocity field data, distinct kinematic regions are found with the Lagrangian coherent structure (LCS) method. The implications of this analysis with respect to heat transfer and related sonochemical applications are discussed.

1 Introduction

The dissipative propagation of acoustic waves can produce streaming flow fields and localized heating. Lord Rayleigh undertook the first theoretical study of acoustic streaming, and many subsequent studies have furthered our understanding (Lighthill 1978). Acoustically induced streaming flows and heating are essential to various applications such as ultrasonic processing and environmental sonochemistry. The streaming-driven convection of the heating is a complex, coupled fluid process. Few previous experimental studies characterize both acoustic streaming and heating. Most of the literature has focused on the velocity measurements of steady acoustic streaming flows using either laser Doppler velocimetry (LDV) or particle image velocimetry (PIV) technique. For example, Chouveton et al. (2000) used PIV to examine the influence of electric power, water depth, and fluid viscosity on the velocity field of a sonochemical reactor. Their results report the velocity increases in a nonlinear manner with increasing electric power and on average decreases with depth and increases with viscosity, below a threshold value. Frenkel et al. (2001) used a PIV measurement of the ultrasound-induced acoustic streaming in order to understand the enhanced uptake of substances from the aquatic medium by fish. They found four distinctive

streaming flow patterns around the modeled fish from their PIV measurements. Loh et al. (2006) used PIV to map the velocity field induced by an ultrasonic vibrator mounted on the bottom of a chamber with a glass top, which served as an upper solid boundary for the velocity field, creating acoustic streaming between the ultrasonic vibrator and the glass plate. A novel aspect of this study is the simultaneous investigation of both surface heating and subsurface vortex structures in an unsteady acoustic streaming flow.

In addition, most previous studies have examined steady streaming flow regimes and neglected the initial unsteady process of acoustic streaming. This initial transient process might be the critical period for various applications of environmental sonochemistry as some chemical reactions occur over short time scales at the beginning of the ultrasound treatment, during which the heating and fluid dynamics are not well understood (Suri et al. 1999; Fu et al. 2007). In this study, understanding of the vortex structure and heating distribution is sought through the identification of developing vortical regions.

Only a few previous studies have attempted combining PIV and IR measurements to investigate the relationship of thermal convection and coherent structures of any flow field (e.g. Volino and Smith 1999 and Gurka et al. 2004). Volino and Smith (1999) were the pioneers in coupling the PIV and IR techniques to study the heat transfer of thermal plumes in a thick layer of fluid. Gurka et al. (2004) investigated the coherent patterns of a turbulent boundary layer flow in a flume using PIV and a Hot-Foil IR imaging technique.

For this unsteady streaming flow, the Lagrangian coherent structure analysis (LCS) is applied in order to gain some insight into the vortex structures. Recently, the LCS approach has been used to investigate the transport structure of unsteady flows. Green et al. (2007) made a comparison between the results from the LCS and Eulerian criteria for coherent vortices in a fully developed turbulent flow. Vétel et al. (2010) used the LCS method to identify vortices from the flow through a smooth axisymmetric constriction in a pipe. Furthermore, the LCS method has been applied to biological and physical flow systems. For example, Coulliette et al. (2007) applied the LCS description to high-frequency radar surface velocity measurements in Monterey Bay to investigate pollution in the bay. Shadden et al. (2009) examined the transport of surface currents based on the relationship between LCS and surface drifter paths in a coastal region. Peng and Dabiri (2009) applied the LCS method to the study of predator–prey interaction in jellyfish feeding. These studies demonstrate that the LCS approach is suitable for the examination of transport processes in unsteady fluid systems.

2 Experimental methods: PIV and IR

Simultaneous PIV and IR measurements of the velocity field and heating field of the transient acoustic streaming flow in a clear acrylic tank (length 50 cm, width 30 cm, and depth 30 cm) filled with degassed, filtered water were made. The center frequency of the acoustic horn was 20 kHz, and a constant 115 watt power setting was applied at specified time intervals. A calibrated, midwave (2.5–5.1 μm) IR camera (Titanium SC7000, FLIR System, Inc., Wilsonville, OR) was used to measure the surface temperature. The positions of PIV and IR cameras for the horizontal plane measurements in the tank are shown in Fig. 1. Both cameras were positioned to capture images from above the tank with overlapping fields of view. The PIV camera was perpendicular to the free surface with the IR camera tilted slightly to avoid reflection from the lens. The IR camera was synchronized with the PIV camera by the PIV synchronizer.

The IR camera was precalibrated, and the uniformity correction factor (due to individual camera variations in gain) was obtained with the commercial software. No extra calibration was needed since the experiments were performed within the factory calibration range.

The position of the horn is shown in the PIV raw image in Fig. 2. The coordinate system was defined such that the $x - y$ plane was the horizontal plane on the free surface. The z axis was defined normal to the free surface with $z = 0$ at the free surface and increasing in the upward direction. The coordinates $x = 0$ and $y = 0$ were set at the lower left-hand corner of the PIV image. The horn was mounted horizontally at the center of the side wall (along the x -axis) with the horn tip pointing in the positive y direction. Five thermocouples mounted in a vertical array were placed 2.5 cm in front of the tip of the horn to measure temperature variations in depth (z direction).

The PIV measurements were made using a TSI Incorporated (Shoreview, MN) PIV system, which consisted of a pair of pulsed Nd/YAG lasers with the power of 120 mJ, a 1,024 by 1,280 pixel complimentary metal-oxide semiconductor (CMOS) digital camera, a synchronizer, and a computer. Each laser operated at 30 Hz, resulting in 60 laser pulses per second. An articulating laser arm was used to deliver the laser beam to the measurement location. The laser light sheet was formed using a cylindrical lens ($f = -25$ mm), and the beam was focused with a spherical lens ($f = 1.0$ m), resulting in a light sheet approximately 1 mm wide. The laser sheet was positioned in the tank from the side, forming a horizontal plane ($x - y$) 1.5 cm below the free surface. The water in the tank was seeded with hollow glass spheres (mean density = 1.1 g/ml) supplied by the TSI. Ultrasound insonification of the fluid at rest followed the initiation of the PIV system and IR camera. The temporal delay between the two images of each PIV image pair was set to be 50 ms, which was chosen to limit the maximum particle motion to roughly 7 pixels, allowing an initial PIV subwindow of 64 by 64 pixels to be used to estimate the particle displacement. The PIV camera took 30 image pairs per second, yielding 30 instantaneous velocity fields per second. A sequence of 1200 image pairs (40 s) were captured.

The reflected laser light from the acoustic horn required additional experimental consideration and care. As seen in Fig. 1, the acoustic horn in the PIV raw image resulted in strong laser light refraction. This high level of light intensity remained roughly constant throughout the experiment and hence was easily identified and eliminated from the PIV raw image by subtracting the minimum intensity of the images from the raw images. Figure 2 shows the minimum image and a typical image with the minimum image removed. Cross-correlation was then applied to the processed image pairs to resolve the instantaneous velocity fields using the PIV software developed by the TSI. Each raw image pair was initially interrogated with a 64 by 64 pixel subwindow. A Gaussian peak fit was used for the subpixel interpolation. The spurious vectors were identified and removed using a local median comparison tool based on the velocity magnitude provided in the TSI processing software. The subwindow size was then reduced to 32 by 32 pixels with the initial velocity field as the estimates. The subwindow size was further reduced to 16 by 16 pixels, resulting in a 127 by 159 grid of velocity vectors for each instantaneous velocity field. Additional smoothing of the velocities was not needed.

3 Lagrangian coherent structures

The Lagrangian coherent structure (LCS) methodology reveals the underlying coherent flow structure in unsteady flows. We note that vortices have been observed in other experimental acoustic streaming studies (Loh et al. 2006), but the application of coherent structure techniques has not been done for these flows. LCS is defined as the local maxima of the finite-time Lyapunov exponent (FTLE) (Shadden et al. 2005). The FTLE field can be calculated from tracer trajectories using PIV velocity data. An advantage of the LCS method is that the FTLE calculation is insensitive to short-term anomalies in the velocity field (Haller 2002). Furthermore, LCS can reveal the vortex's boundaries. Detailed discussion and calculation of the FTLE and identification of LCS are given in Shadden et al. (2005,

2006). We refer the reader to the literature for a more comprehensive treatment (Green et al. 2007; Pen and Dabiri 2009).

A publicly available Matlab package developed by Dr. John. O. Dabiri of the California Institute of Technology was used for the FTLE calculations in this study (Peng and Dabiri 2009; <http://dabiri.caltech.edu/software.html>).

4 Results

4.1 Vortex pair

A representative instantaneous velocity field is shown in Fig. 3. A flow is apparent along the centerline of the horn (note that the center of the acoustic horn is 4.84 cm below the PIV measurement plane). Vortices are generated approximately along the centerline of the horn and propagate in the positive y direction (away from the horn tip). The main vortex pair grows with time, and its length scale becomes comparable with the length of the horn (6 cm). This vortex pair is also found in a control case for the same conditions except without the thermocouple array. We conclude that it is an intrinsic streaming feature (Chouvellon et al. 2000) independent of the thermocouples. Flow disturbances from the thermocouple array can induce small-scale vortices on the order of 3 mm (rod diameter) downstream, and these do not significantly influence the primary fluid dynamics under investigation.

FTLE measures the separation rate in the flow such that the local maxima of separation rate (i.e., LCS) can be characterized as the material surface between kinematic regions of the flow. Depending on the time duration of the integration, we are able to examine the entire transient process or a specific time period in a single plot. LCS not only shows the temporal evolution of the vortices but also shows the spatial location of the vortex boundary over specific periods of time. The FTLE fields were calculated using forward integration in this study. With forward integration, the LCS from the FTLE is called repelling LCS (Shadden et al. 2005). The FTLE fields integrated from $t = 20\text{--}30$ s and from $t = 30\text{--}40$ s are shown in Fig. 4a, b, respectively. Fig. 4a indicates that the LCS is not fully developed during the first 30 s, while the main LCS within the measurement area can be seen in Fig. 4b. The LCS curves are readily extracted from FTLE contour plot integrated from $t = 30\text{--}40$ s.

The FTLE plots shown in Fig. 4 reveal the ridges or barriers corresponding to the vortex structure in the velocity field. As the vortex pair develops, the FTLE is mainly concentrated between the boundary of the vortex pair. The open loops of the high FTLE refer to the propagating directions of the two main vortices as the fluid trajectories evolve rapidly within this ten-second period. The FTLE is also concentrated along the centerline of the horn tip. The LCS (the local maxima of the FTLE in near the center line of the horn), which serves as the material surfaces of the flow, divides the kinematic regions into the left and the right in the field of view. Therefore, the flow near the centerline of the horn is defined as being repelled from the horn (Shadden et al. 2005).

4.2 Unsteady vortex structures and heat transfer

The PIV plane is 1.5 cm below the free surface while the temperature field is on the free surface. Assuming the boundary layer approximation on the free surface, the velocity component normal to the free surface w (in the z direction) approaches zero as it is close to the free surface. The order of magnitude of the spatial velocity components u and v between the PIV plane and the temperature plane is the same. Thus, the order of magnitude of the vorticity ω_z between the two measurement planes is approximately equal at a given time. In addition, the temperature results measured with the thermocouples indicate that the temperature difference between the PIV plane and IR plane is small ($\approx 0.01^\circ\text{C}$). Hence, the results evaluated from the PIV measurement can be assumed as those corresponding to the

temperature fields. We can examine the coupled, spatial, and temporal evolution of these processes.

The main heating source of the flow is due to dissipative effects on the acoustic field generated by the horn. The surface temperature change (ΔT) is shown as the difference in temperature between the IR frames at specific times and the initial ambient conditions (Fig. 5).

Selected superimposed frames (snap shots) of the instantaneous velocity vector field superimposed on the temperature field are shown in Fig. 6. Continuous heating near the tip of the horn generates a thermal disturbance in the flow, which diffuses within the flow structures. In addition, the main vortex pair facilitates convective heat transport. The eddying and shearing regions in the flow are often associated with the high-temperature regions. The surface temperature field also shows the heating of the horn at the sidewall, which is transported within a local circulating region as seen at the lower right corner of the field of view in Fig. 6.

The overall heat transfer process was examined using the LCS obtained from the FTLE plots discussed earlier. The local maximum of FTLE (LCS) forms repelling material lines that act as kinematic barriers to transport (Shadden et al. 2005). This LCS obtained from the integration over 10 s of the PIV velocity data is superimposed with the spatially averaged temperature field over the same time intervals in Fig. 7a–c. It is apparent that the temperature is higher at the heat locations near the horn tip and the side wall of the tank in the lower right-hand corner of the field of view. Since fluid particles on one side of the LCS will recirculate on the same side, the heating patterns should coincide with the regions bounded by the LCS (i.e., a cold region and hot region are separated by LCS as shown in Fig. 7b, c). More specifically, the high-temperature area at the lower right corner is roughly bounded by the LCS in Fig. 7c. The temperature is relatively low at the lower left-hand side because the well established LCS locations along the centerline of the horn serve as the barrier between the left and right sides in the temperature field. The short time duration of this experiment is not sufficient for the heating and streaming to reach steady state conditions. Note that even in steady state the temperature does not become completely uniform as long as the horn is running.

The use of LCS for tracking heat transport is an unexplored topic. Comparing the LCS with the surface temperature field, it is evident that the heat is transported along the LCS as shown in Fig. 8. The high-temperature structures with the circle in the temperature field (Fig. 8a) closely resemble the LCS (Fig. 8b). LCS has been outlined in terms of the stretching of fluid particles over time (Shadden et al. 2005), and we might describe this as ‘stretching’ of the localized heating. It is intriguing that the LCS tracks heat transport as well as providing a kinematic boundary for this flow. We note the relatively long time interval in which the LCS follows the indicated trajectory in subsequent frames. Closer inspection suggests the role of the vertical metal rod, which supports the thermocouples. It has longer temperature retention at a fixed location. This is seen in Fig. 2a [bright spot at (10 cm, 10 cm)] and Fig. 8a at the same location. This localized ‘hot spot’ slightly influences the convective flow pattern, and LCS has sufficient sensitivity to discern this subtle development.

5 Discussion

The unsteady convective heat transfer associated with acoustic streaming can rigorously examined with the LCS using the PIV velocity data superimposed on the temperature field. Kinematic regions of the flow can be identified as well as the role of the vortices on the

evolving heat transfer. The potential but minor drawback of the LCS approach is that the FTLE calculations are computationally intensive because of the large amount of PIV velocity data required for trajectory integration.

Acoustic horns are commonly used in industrial sono-chemistry reactors. Our results suggest that the distinctive spatial characteristics in the unsteady acoustic streaming flow may result in nonhomogeneous reaction processes in the reactor. Studies have shown that the streaming and heating generated by ultrasound are able to degrade harmful substances such as estrogen hormones and other chemicals in water (e.g. Suri et al. 1999; Fu et al. 2007). A limiting underlying assumption of most industrial sono-chemistry applications to the acoustic streaming flows is the spatial homogeneity of the reaction process. However, the acoustic streaming flow field is composed of characteristic flow regions such as eddying and shearing regions (Fig. 6). These distinctive regions are likely to have localized effects on chemical reactions in sonochemical reactors. Therefore, characterization of flow field regions is an important fundamental research step in design optimization for sonochemical reactors used in various treatment processes. Enhanced performance of sonochemical reactors might be achieved by maximizing high shearing fluid motion regions with a specific design based on in-depth knowledge of the flow field.

6 Conclusions

In this paper, the dependence of surface heat transfer on subsurface coherent structures of acoustic streaming based on the LCS approach was investigated using PIV and IR imaging measurements. The instantaneous velocity vector fields reveal the formation and propagation of a vortex pair along the centerline of the acoustic horn. The length scale of the vortex is on the order of the length of the acoustic horn. Localized heating near the horn tip creates forced convection in the flow field. LCS divides the acoustic streaming field into three distinct regions: the corner, the vortex, and the horn's centerline. LCS approach is a useful method to identify the temporal evolution of vortices within an acoustic streaming field. Knowledge of the spatial surface temperature field provides physical insights into the subsurface vortex structures. These preliminary results suggest that the temperature structures resemble the LCS when a localized higher temperature spot coincides with the LCS path. Therefore, the LCS not only serves as the kinematic boundary in the flow but also characterizes how heat is transported. This study demonstrates that the identification of vortex structure using the LCS is a robust and efficient way to identify kinematic regions in acoustic streaming flows.

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Fig. 1. The experimental setup for simultaneous PIV and IR measurements. Temperature measurements in depth reveal the IR and PIV image planes that can be approximated as the same spatial location

Fig. 2.

a The minimum image of the PIV data set showing the acoustic horn's position. **b** A typical image with the minimum image removed

Fig. 3.

PIV resolved instantaneous velocity field at $t = 20$ s. The asymmetry in the vortex pair is attributed to surface imperfections due to wear at the horn tip

Fig. 4. FTLE plot integrated over 10 s of the PIV velocity data and the corresponding initial velocity field for each FTLE calculation. **a** integration from $t = 20$ – 30 s, **b** $t = 30$ – 40 s

Fig. 5. Surface temperature change (ΔT , °C) from the IR image showing the heat generation from the acoustic horn, reveals conduction on the sidewall. However, this does not significantly influence the results in the center of tank in this study

Fig. 6.

Instantaneous velocity field superimposed on the instantaneous surface temperature field (ΔT , $^{\circ}\text{C}$). **a** at $t = 16.7$ s, **b** $t = 20$ s, **c** $t = 23.3$ s, **d** $t = 26.6$ s, **e** $t = 30$ s, **f** $t = 33.3$ s

Fig. 7.

LCS (*black line*) integrated over 10 s of the PIV velocity data superimposed on the spatially averaged temperature field ($\langle \Delta T \rangle$, $^{\circ}\text{C}$) over the corresponding time period of the instantaneous temperature field for the integration times. **a** from $t = 10\text{--}20$ s, **b** $t = 20\text{--}30$ s, **c** $t = 30\text{--}40$ s

Fig. 8.

The transport of the localized heating (*dashed circle*) corresponds with the LCS for an instantaneous temperature field. **a** instantaneous temperature field (ΔT , °C) at $t = 33.3$ s, **b** LCS from $t = 30$ – 40 s