Fig. 4. It is clear from Fig. 4 that τ_9 follows a trend similar to the trend of the variation of σ_9.

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Two-Dimensional Shear-Layer Entrainment and Interface-Length Measurements

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Introduction

LARGE-SCALE vortices have been studied extensively for many years. The development of these vortices is viewed as a key mechanism in the promotion of macroscale mixing that creates the environment in which microscale mixing can induce chemical reactions. In the present study, a novel approach was utilized to investigate the effect of vortex roll-up on entrainment, interface length, and mixing. The unique interface-tracing technique developed and demonstrated in this investigation allows direct study of the mixing and reaction along the interface. Entrainment of fluids from both sides of the mixing layer was measured after locating the interface boundary. Thus, the mixing and reaction enhancement can be directly compared with the measured interface elongation for the first time. This allows direct evaluation of the efficiency of mixing enhancement by increasing the interface length through vortex roll-up.

This Note will provide a brief description of the experimental setup. (Details can be found in the original full length paper.[1]) Two-dimensional vortices are generated from a splitter plate that separates two parallel streams of air, one high speed, one low, contained within a 12.7-cm-square Plexiglas duct. The splitter plate divides the duct into two equal areas. Dry air is used on both sides. A technique known as reactive Mie scattering[2] is used to visualize the vortical flow. Air on the high-speed side of the splitter plate is passed over a liquid $TiCl_4$ bath, collecting $TiCl_4$ vapor. Air on the low-speed side of the splitter plate is passed over a water bath, collecting water vapor. The $TiCl_4$ in the higher velocity airflow reacts with the moist air on the low-velocity side of the flow, forming micron-sized TiO_2 particles that follow the gas flow and distinctly mark the molecular interface of the two airstreams. The velocity of the air on the high-velocity (left) side of the flow was 0.94 m/s and that on the low-velocity (right) side was 0.47 m/s. Vortex formation and shedding are driven by acoustic stimulation of the low-speed flow, which can be controlled with great consistency, which is essential for phase-locked measurements. Some data were obtained in undriven shear layers with additional measurements being made in identical flows driven at 15, 20, and 25 Hz. The flowfield is recorded as a digital image on a portion of a 1024 × 1024 diode array. Typically, the image size was 250 × 1024 pixels, with the 1024 pixels oriented parallel to the flow direction. The light source is the frequency-doubled output (532 nm) of an Nd:YAG laser. The image is collected with a charge-coupled device (CCD) camera and analyzed in its original form.

Results and Discussions

Figure 1 shows, at six different phase angles, a two-dimensional shear layer being driven at 20 Hz. These images were obtained by increasing the delay time between the generation of the vortex and the CCD camera exposure. The excellent repeatability of the driven flow makes phase-locked measurements possible.

A computer algorithm was developed for tracing two lines of constant intensity on the shear layer in the digitized images. These constant-intensity contour lines are illustrated in Fig. 2. These two lines mark interface surfaces for the fluid on the left and right sides of the flow with the TiO_2 product. The area between the two lines thus represents the mixed region, or the region where the TiO_2 product resides. The phase-locking capability allows vortices to be followed in a Lagrangian frame of reference because the flow is phase locked with the CCD camera. Since individual vortices were singled out in the flow, a method was needed for establishing a bounded region within which to measure areas and interface lengths. The method selected was to draw a box around the vortex with the top and bottom edges of the box being located halfway between adjacent vortex centers near the stagnation points. The sides of the box were drawn tangent to the extreme edges of the vortex. The area and interface lengths were then calculated with the computer algorithm developed for that purpose. From these measurements, the entrainment and resultant interface length were derived and studied parametrically as a function of driving frequency.

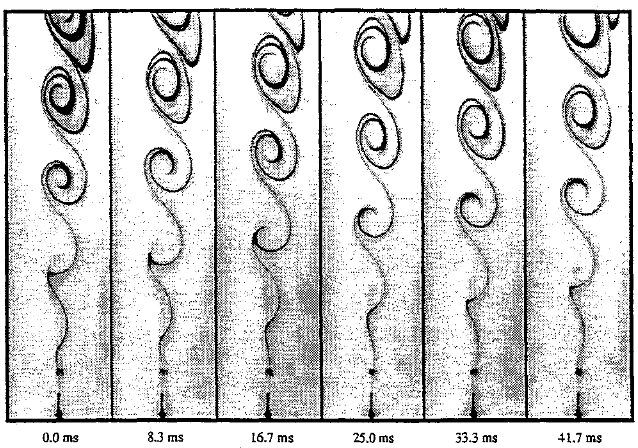

Fig. 1 Phase-locked images of a two-dimensional shear layer driven at 20 Hz.

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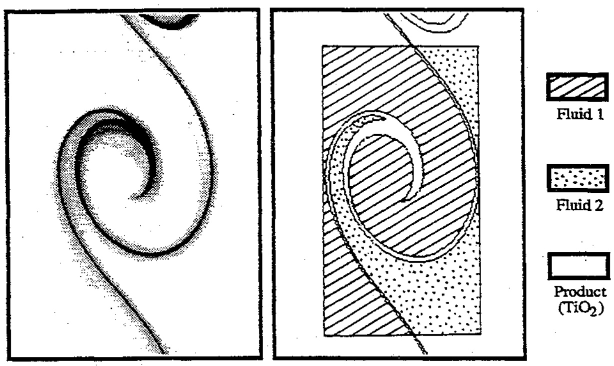

2(a) Digital Image 2(b) Intensity Contour Lines

Fig. 2 Definition of interfaces and areas from contour analysis.

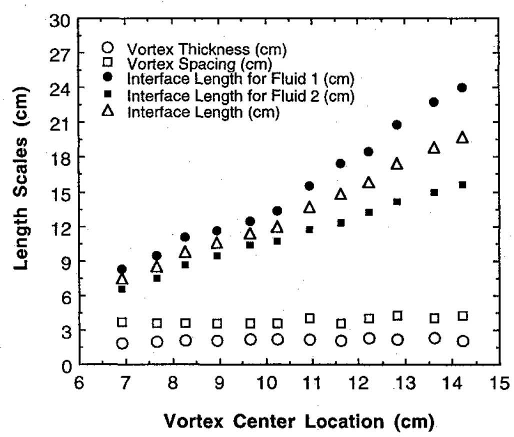

Fig. 3 Measured vortex length scales for 20-Hz case.

To account for the effect of individual vortex roll-up on interface length, the following convention was followed. The width of the vortex was measured as the spanwise distance between lines drawn tangential to the edges of the vortex, i.e., the width of the box shown in Fig. 2b. Typically, the vortex length is defined as the distance between the leading stagnation point and the trailing stagnation point of a given vortex. In this study, the central point between two adjacent vortices was used rather than the actual stagnation point. Therefore, the vortex spacing figures described in this paper were obtained by measuring the distance between the leading central point and the trailing central point of a vortex, that is, the length of the box shown in Fig. 2b. This vortex spacing was taken as the reference length scale for the computation of the interface elongation factor for each vortex.

Figure 3 shows the measured vortex interface length, width, and spacing as a function of the downstream location of the associated vortex. The driving frequency was 20 Hz. Examination of the interface length indicated that the interface between fluid 1 and the product was longer than the interface between fluid 2 and the product. That is, the interface of fluid 1 with the product region grew at a faster rate than the interface of fluid 2 with the product region. This implies that the high-velocity side of the flow contributed more fluid to the vortex, and this observation supports the idea of asymmetric entrainment into a shear layer.[3]

Figure 4 shows the interface length of fluid 1 with the product area for individual vortices normalized by the associated vortex spacing. These normalized values (elongation factor) indicate the degree of increased interface length over a case in which no roll-up was present. The data indicate that the interface length increases the most when the flow is driven at 25 Hz. The elongation factor decreased with lower drive frequencies. Clearly, the acoustical driving has a significant effect on the onset and degree of roll-up as well as the shape of the vortices. The areas of fluid 1 and fluid 2 and the product as functions of downstream location were also measured. Based on the data, the entrainment ratio of fluid 1 to fluid 2 yields a value of 2.0.

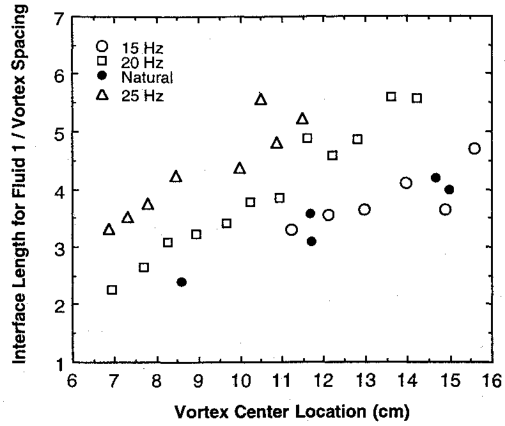

Fig. 4 Normalized interface length (elongation factor) for fluid 1.

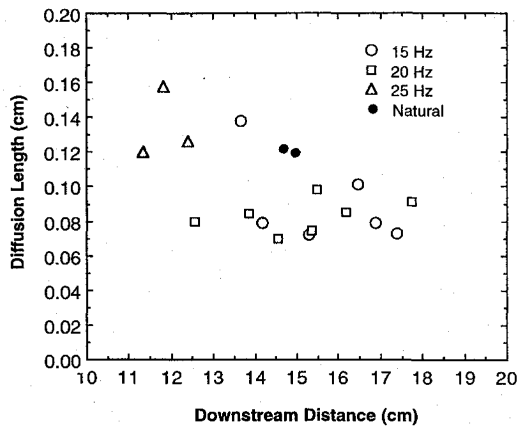

Fig. 5 Measured transverse diffusion thickness.

Comparisons can also be performed on the basis of the entire shear layer rather than individual vortices. The total interface length is measured from the tip of the splitter plate to the specified downstream location. One way of examining the correlation between the product area and the elongated interface is to obtain the ratio of these two quantities. This ratio is expressed in units of length and is equivalent to the overall transverse diffusion thickness by definition. This diffusion length is plotted in Fig. 5. The diffusion thickness for the 20 Hz case is fairly constant at ~0.08 cm. This indicates that the area of mixing or reaction is linearly proportional to the interface length. The 25-Hz case yields the largest transverse diffusion length, and the 15-Hz case yields the smallest.

Acknowledgments

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