

Cavitation phenomena occurring due to interaction of shear layer vortices with the trailing corner of a two-dimensional open cavity

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The onset of cavitation in a high Reynolds number, two-dimensional open cavity shear flow occurs on top of the cavity trailing edge, well before it appears in the shear layer. However, the cavitation there disappears periodically, even at pressures that are much lower than inception level and when cavitation expands to the shear layer upstream. The primary cause for this phenomenon is periodic elimination of the pressure minimum on top of the corner due to flow induced by shear layer vortices arriving to the trailing edge of the cavity. Both the location of and conditions for cavitation inception agree with measured mean and fluctuating pressures performed using a novel technique for determining instantaneous spatial pressure distributions. © 2008 American Institute of Physics. [DOI: 10.1063/1.2897320]

Due to their impact on noise, vibrations and erosion, cavitation phenomena have been investigated extensively in a variety of flows.^{1,2} However, to the best of our knowledge, there is very little literature about the pressure field^{3,4} and no information on occurrence of cavitation in a turbulent shear flow developing past an open cavity, in spite of the extensive work on this geometry.^{3–6} Knowledge of the pressure distribution is of fundamental importance for understanding the inception and subsequent development of cavitation. Motivated by the lack of appropriate means for measuring pressure distributions, we have recently developed an optical technique that can measure the instantaneous spatial pressure distribution over a sample area nonintrusively.⁷ This method utilizes four exposure particle image velocimetry (PIV) to measure the distribution of in-plane projection of the material acceleration and integrating it spatially to obtain the pressure distribution. Since cavitation is an effective method for detecting pressure peaks, it can be used for “validating” the pressure measurements, where no other technique is available. In this paper we present unexpected cavitation phenomena in an open cavity shear layer.

The experiment is conducted in a small water tunnel (Gopalan and Katz⁸), using setup sketched in Fig. 1. The acrylic 38.1 mm long, 50.8 mm wide, and 30.0 mm deep cavity is installed in the 50.8 (width) $\times$ 63.5 (height) mm test section. The setup consists of a mild contraction ramp leading to the cavity, followed by a mild diffusing ramp. There are no significant pressure minima upstream of the cavity or flow separation downstream. The mean velocity above the cavity U_∞ ranges between 5 and 10 m/s, corresponding to Reynolds numbers based on cavity lengths L of 1.7×10^5 and 3.4×10^5 . Tripping grooves at the beginning of the contraction ramp ensure that the separating boundary layer at the beginning of the cavity is turbulent (data not shown), with momentum thickness Reynolds numbers ranging between 1096 and 1778.

To record four exposure PIV images, we use two $2K \times 2K$ digital cameras with interline image transfer

(Kodak ES4.0), as well as two pairs of dual-head Nd:YAG lasers whose beams are orthogonally polarized. Vector spacings are $100 \mu\text{m}$ at $U_\infty = 5 \text{ m/s}$ and $200 \mu\text{m}$ at $U_\infty = 10 \text{ m/s}$. Conservative uncertainty estimates in instantaneous variables are velocity $< 1.5\%$, acceleration $< 40\%$, and pressure $< 6\%$. Uncertainties in mean variables are velocity $< 0.05\%$, vorticity $< 4.0\%$, cavitation index 0.04–0.1, and pressure $< 0.2\%$. High-speed images are recorded by Photron FASTCAN-ultima camera at 8000–30 000 frames/s.

Observations on occurrence of cavitation reveal that the first site of cavitation inception is located on top of the

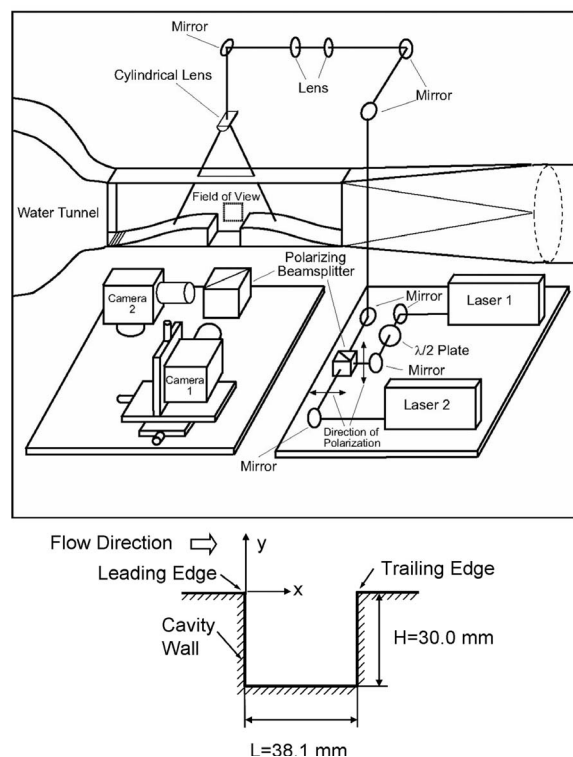


FIG. 1. Test section and optical setup.

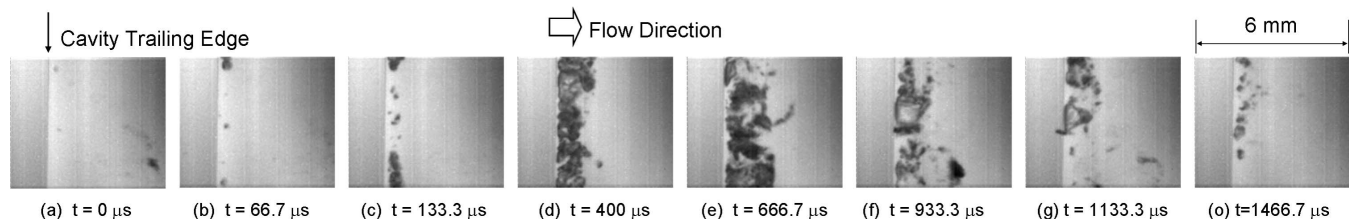


FIG. 2. Sample top view high-speed camera images of cavitation inception above the cavity trailing edge, recorded at 30 000 frames/s. $U_\infty = 10$ m/s, $\sigma = 0.9$ (inception level), and the water is saturated with air.

downstream corner of the cavity, regardless of the free stream speed and dissolved air content in the water. Furthermore, the cavitation is persistently periodic, growing, and disappearing, typically at a frequency of 300 Hz (at $U_\infty = 10$ m/s), although the periods vary. Figure 2 shows a sequence of representative images, recorded at 30 000 frames/s during the first half of a typical cavitation cycle, illustrating the incipient, growth, and collapse of bubbles. Here, the cavitation index is $\sigma = 0.9$, where $\sigma = (p_\infty - p_v) / (0.5\rho U_\infty^2)$, p_∞ is the mean pressure just upstream of the cavity, p_v is the vapor pressure, and ρ the water density.

With decreasing mean pressure, the size of cavitation above the corner increases, and for $\sigma < 0.6$, cavitation starts appearing in the shear layer upstream of the step. For $\sigma < 0.4$, cavitation persistently appears within the shear layer eddies and travels with them. At this pressure, the cavitation on top of the trailing edge appears like periodically growing and collapsing (disappearing), “giant” (> 1 cm) glossy vapor pockets. This process always starts and ends at the corner. As demonstrated by two examples in Fig. 3, the glossy cavitating region appears to be large when the vapor-filled shear layer eddies are located away upstream from the trailing edge, and disappears when the cavitating vortices are located close to the corner. This persistent phenomenon suggests a relationship between the location of shear layer eddies, the pressure field, and cavitation above the corner. The typical distance between cavitating eddies is $0.26\text{--}0.40L$, consistent with velocity measurements of noncavitating flow. The convection speed of the eddies is $c = 5\text{--}6$ m/s, as measured from the high-speed images. The corresponding frequency is $f = 300\text{--}320$ Hz (Strouhal number, $St = fL/U_\infty$, of $1.14\text{--}1.22$), in agreement with data of a surface pressure transducer located at $x/L = 1.27$ (not shown), and with theoretical predictions by Martin *et al.*⁹ and Blake,¹⁰ using

$St = (n + 0.25)(c/U_\infty)$, with $n = 2$, i.e., simultaneous presence of two vortices in the shear layer.

The occurrence of wall pressure minima above a corner as eddies generated by an upstream shear layer travel along the surface is reported in Tang and Rockwell.³ For geometry similar to the present setup, but a Reynolds number lower by an order of magnitude, the amplitudes of their wall pressure minima, expressed as $C_p(t) = [p(t) - p_\infty] / (0.5\rho U_\infty^2)$, are in the $0.12\text{--}0.34$ range, i.e., lower than values expected from our cavitation tests. The discrepancy is reasonable since their shear layer is quasilaminar and does not contain fully developed turbulent eddies. Nonetheless, their insightful flow visualization is consistent with the present observations. Figure 4 shows distributions of mean horizontal and vertical velocity components at $U_\infty = 5$ m/s. The corresponding mean pressure is shown in Fig. 5 along with probability density functions (PDFs) of the fluctuating pressure at selected points. Acceleration of mean flow, from the flow impingement region upstream of the corner, decreases the mean pressure from a peak value upstream of the trailing edge to a minimum above the corner. The location of cavitation inception is consistent with the point of minimum pressure.

To measure cavitation inception indices (σ_i), we slowly lower the pressure at a fixed velocity and record the pressure above the leading edge of the cavity ($p_{\infty i}$) when cavitation first appears. Results presented in Fig. 6 show that σ_i varies with dissolved air content, which in turn affects the distribution of cavitation nuclei.² For nuclei-rich “weak water,” σ_i is about 0.9 and does not vary significantly with velocity. The instantaneous pressure minimum above the corner ($C_{p\min}$), i.e., the sum of a -0.2 mean pressure minimum and a negative PDF tail of about -0.7 , agrees with the conditions for cavitation inception, $C_{p\min} = -\sigma_i$.

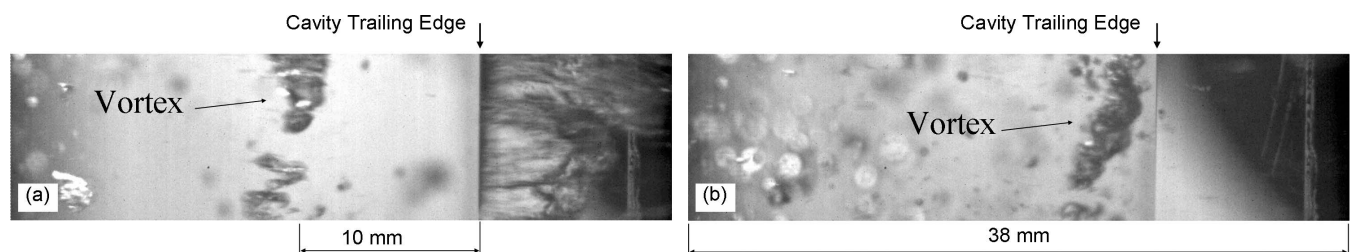


FIG. 3. Sample top view high-speed camera images of developed cavitation, showing (a) extensive cavitation above the corner when the cavitating vortex is located 10 mm upstream of the corner, and (b) disappearance of this cavitation when the vortex is located near the corner. $U_\infty = 10$ m/s and $\sigma = 0.37$, recorded at 8000 frames/s for cavity shear flow of weak water.

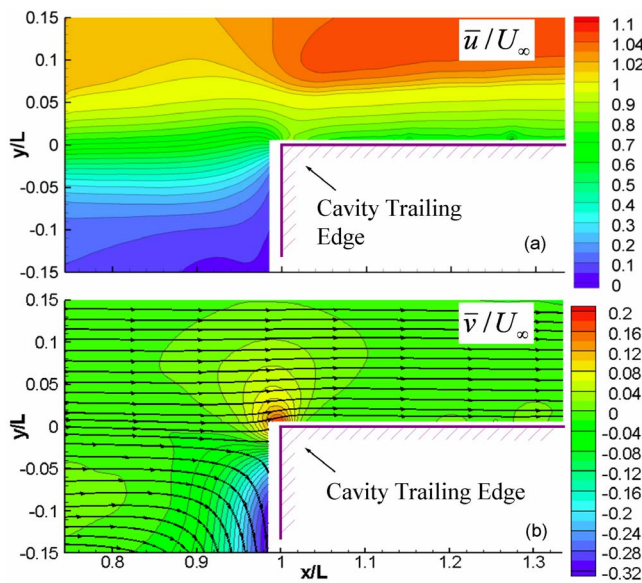


FIG. 4. (Color online) Time-averaged velocity distributions around the cavity trailing corner along with absolute streamlines in the lower plot. $U_\infty = 5$ m/s.

For $\sigma < 0.6$, expansion of cavitation upstream into the shear layer also agrees with the pressure fluctuation statistics, shown for $U_\infty = 5$ m/s in Fig. 5, along with distribution of rms values at $U_\infty = 10$ m/s in Fig. 7. In the shear layer, the highest pressure fluctuations occur just upstream of the cavity trailing edge, close to the point of maximum mean pressure. At $\sigma = 0.37$, heavy cavitation occurs within the spanwise vortices over the entire shear layer (Fig. 3).

Our suspicion that the periodic appearance and disappearance of cavitation above the trailing edge are correlated with flow-induced changes to pressure has led us to examine relationships among instantaneous pressure and flow structure. Two samples comparing the flow and velocity profiles during periods of high and low pressures above the corner are presented in Fig. 8. The pseudostreamlines superimposed on the pressure distribution are obtained by subtracting half

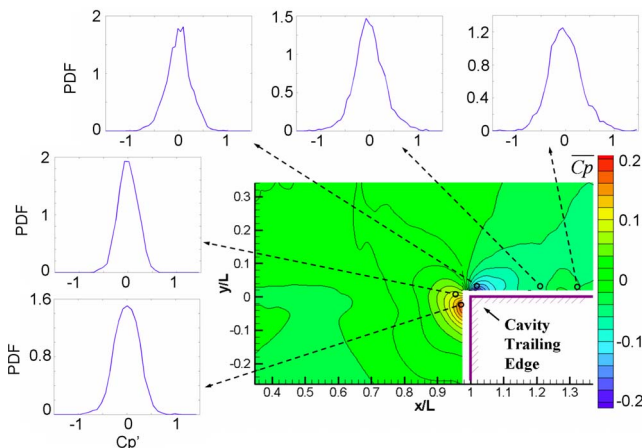


FIG. 5. (Color online) Time-averaged pressure distribution and PDFs of pressure at selected locations around the trailing corner of the cavity. $U_\infty = 5$ m/s.

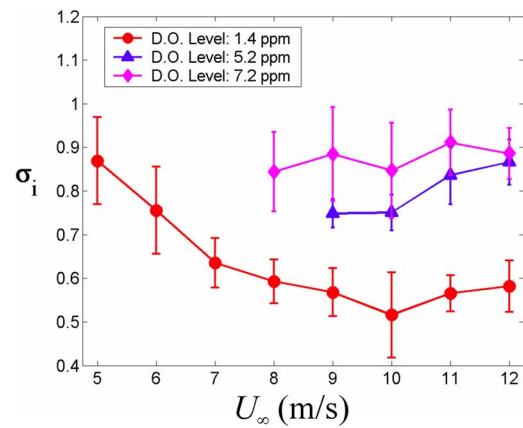


FIG. 6. (Color online) Cavitation inception indices at different dissolved oxygen levels.

of the free stream velocity at every point. Clearly, low instantaneous pressure above the corner occurs when one shear layer vortex is located “far” upstream of the corner and another one seems to be traveling above the corner, most likely enhancing the pressure minimum there [Figs. 8(c) and 8(d)]. High instantaneous pressure above the trailing edge occurs when the shear layer eddy is located just upstream of the corner [Figs. 8(a) and 8(b)], consistent with the cavitation images (Fig. 3). The downwash induced by this eddy reduces the streamline curvature above the corner, eliminating the pressure minimum there. The signatures of these eddies are also evident from the velocity profiles [Fig. 8(e)].

We have tried several criteria for conditionally sampling the data to show the relationship between pressure and flow structure. A simple approach is to detect periods of downwash based on the sign of the vertical velocity component (V), spatially averaged over the sample area denoted by black box in Fig. 9. Distributions of the conditionally sampled pressure and spanwise vorticity as well as comparisons of several velocity profiles are presented in Fig. 9. During downwash, $V < 0$, a (phase averaged) vortex is located very close to the trailing edge, and the conditionally averaged pressure above the trailing corner is relatively high [Figs. 9(a) and 9(b)]. For $V > 0$, the shear layer eddy is lo-

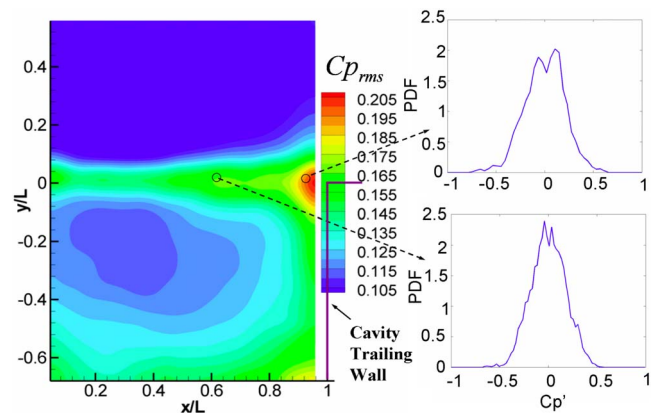


FIG. 7. (Color online) Distribution of rms pressure and PDFs of pressure in the shear layer at $U_\infty = 10$ m/s.

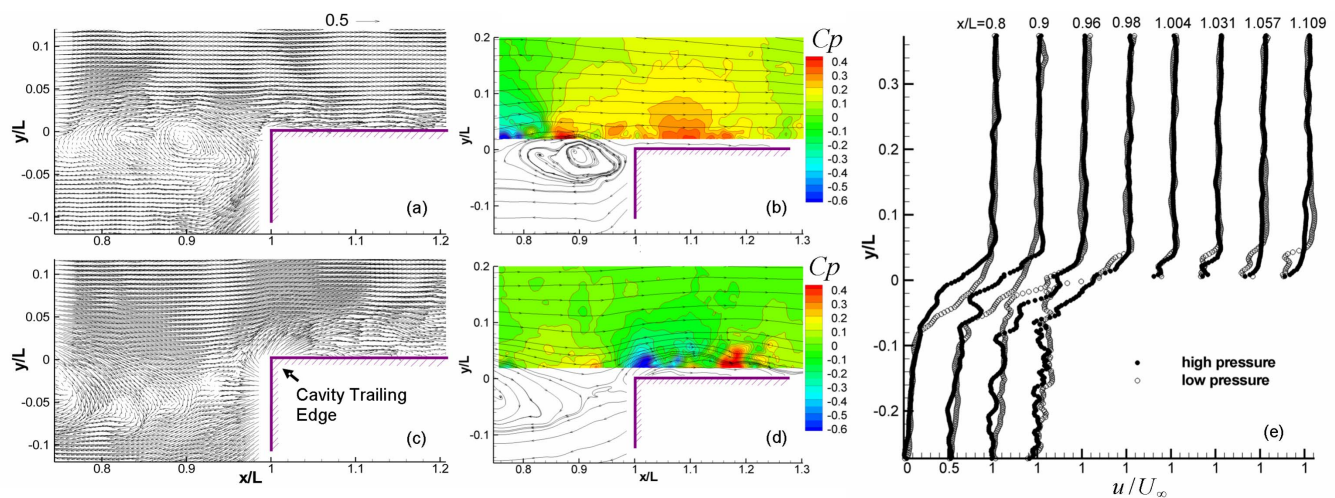


FIG. 8. (Color online) Sample (a) instantaneous velocity vectors, skipped at every other grid point, after subtracting $0.5U_\infty$ ($U_\infty=5$ m/s); (b) the corresponding pressure distributions during period of high pressure above the corner; (c) instantaneous velocity and (d) the corresponding pressure distributions when there is a pressure minimum above the corner; (e) comparison of corresponding streamwise velocity profiles whose locations are indicated on top.

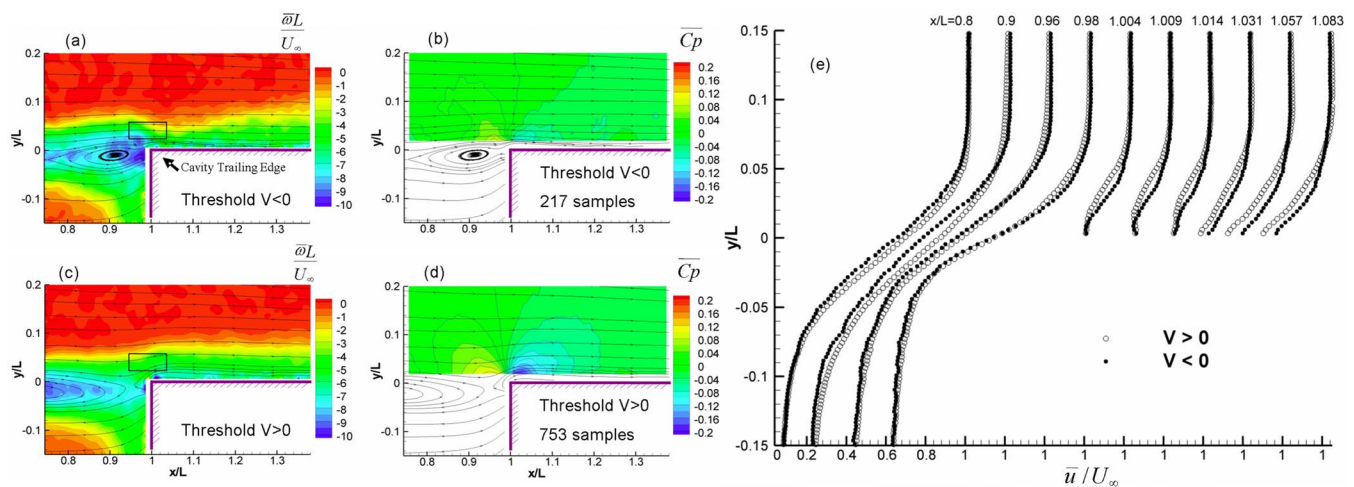


FIG. 9. (Color online) Conditionally averaged distributions of (a) spanwise vorticity and (b) pressure when $V < 0$ in the area indicated by the black rectangle; (c) spanwise vorticity and (d) pressure for $V > 0$; and (e) corresponding comparisons of mean streamwise velocity profiles. $U_\infty=5$ m/s.

cated further upstream, while the vorticity above the corner is elevated, and the conditionally averaged pressure has a minimum [Figs. 9(c) and 9(d)]. Both streamline curvature and presence of eddies above the corner contribute to the pressure minimum. The velocity distributions [Fig. 9(e)] show the associated differences in shear layer profile upstream of the corner, as well as the reduction in near-wall momentum due to the presence of another vortex above the corner. These trends qualitatively agree with the surface pressure measurements of Tang and Rockwell.³ Clearly, the traveling shear layer eddies cause substantial periodic variations in pressure and resulting cavitation above the trailing edge of the cavity. The periodic expansion and disappearance of cavitation persist even when the shear layer eddies are cavitating.

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