An Experimental Study of Sheet to Cloud Cavitation

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ABSTRACT

A 2D convergent-divergent test section was built to study experimentally sheet cavitation followed by bubble cloud formation. Flow visualizations and pressure measurements enabled correlating high speed photography observations with the pressures on the cavitating surface. These indicate that the frequency of the recurring sheet cavity decreases with increased inlet flow velocity. As the inlet velocity increases, the flow structure changes from vortex shedding with entrapped thin cavities, to a sheet cavity with a reentrant jet producing bubble cloud shedding, to a shock dominant cavity collapse flow regime. The two-phase bubbly flow shock front moves upstream at a speed higher than the local sound speed, creating a pressure surge clearly measured as the shock front passes over a pressure gauge. The sheet cavity breakdown during collapse leaves behind vortical bubble clouds.

INTRODUCTION

Sheet cavitation occurs over a lifting surface when the pressure drops to the vapor pressure over a large portion of this surface. The cavity then fills with vapor. As the cavitation condition becomes more severe, cavity length oscillation, unsteadiness, and shedding of vapor clouds take place. These periodic sheet to cloud cavitation events can have deleterious effects on the performance of marine propellers and hydrofoils (Brennen, 1995, Chahine and Hsiao, 2000).

Many authors have attributed the occurrence of cloud cavitation to the development and dynamics of reentrant jets, which move upstream under the cavity and then break it into two pieces (Furness and Huttib, 1975; Lush and Skipp, 1986; Kubota et al.,1989; de Lange, 1996, Pham et al.,1999; George et al.,2000; Callenaere et al.,2001). By blocking the reentrant jet with an obstacle, the periodic shedding could be prevented (Kawanami, 1997). Adverse pressure plays an important role in the formation of the reentrant jets (Callenaere, et al 2001; Gopalan and Katz, 2000; Laberteaux and Ceccio 2001).

It has also been noted that the cavity closure line formed by the reentrant jet is perpendicular to the flow direction for two-dimensional cavities. However, the orientation of the reentrant jet in three-dimensional cavities depends strongly on the span wise geometric variations of the objects (Crimi, 1970; Bark, 1985, 1986; Ihara, et al, 1989; de Lange 1996). Then, the periodic shedding could be affected or prevented from occurring (Forth et al, 2008, Laberteaux and Ceccio, 2001).

Measurements of the void fractions in the cavity and the clouds have been attempted (Stutz & Reboud, 1997 a, b; Stutz and Legoupil, 2003; Coutier-Delgosha et al., 2007). However, the measured quantities varied significantly from one study to another due to the complexity of flows. More recently, extensive studies using X-ray were achieved by Ganesh, Makiharju, and Ceccio (2015). In their study, in addition to reentrant jet observation, condensation shock waves were observed and were associated with strong periodic cloud shedding and collapse.

In this paper, we describe results from experiments conducted in a divergent-convergent test section in an effort to add information to existing studies and to provide essential data to numerical modeling, including flow visualizations and pressure measurements in order to develop a better understanding of the physics behind sheet to cloud cavitation.

EXPERIMENTAL SETUP

A sketch of the test section is shown in Figure 1 with the main dimensions in the top pane and a sketch of the overall setup in the bottom pane. The flow passage in the acrylic test section is formed using profiled top and bottom inserts sandwiched between two side walls 2.22 cm (0.875”) apart to enable good visualization. The inlet and outlet sections have the same dimensions: height 10.16 cm (4”) and width 2.22 cm (0.875”). When designing the convergent-divergent a small flat region 1” long was placed in the minimum cross sectional area between the convergent and divergent sections of the profile to enable slower transition to a
large cavity and facilitate observation as the velocity is increased. Four pressure transducers along the diverging section, labeled from T1 to T4, are used to monitor the acoustic signature of the cavitation.

The liquid flow is driven by a 15 HP pump (Goulds Model 3656), which is capable of a flow rate of 2.16 m$^3$/min (570 gpm) at 180 kPa (26 psi). In this setup the inlet velocity can reach 15.4 m/s. Instrumentation is provided for flow rate and pressure measurements. High speed photography is used to visualize the flow through the test section.

**Figure 1:** Sketch of the test section with main dimensions and pressure transducer locations (top) and overall experimental setup (bottom).

INLET PRESSURE AND CAVITATION NUMBER

The inlet pressure, $P_{\text{inlet}}$, plotted versus the inlet flow velocity, $V_{\text{inlet}}$, is shown in Figure 2. As illustrated in the figure, for conditions $V_{\text{inlet}} \geq 10$ m/s, $P_{\text{inlet}}$ increases proportionally with $(V_{\text{inlet}} - 2.97)^2$ as the trend line indicates. Figure 3 shows the corresponding cavitation number,

$$\sigma = \frac{(P_{\text{inlet}} - P_v)}{(0.5 \rho V_{\text{inlet}}^2)}.$$  \hspace{1cm} (0)

CAVITATION INCEPTION AND VORTEX SHEDDING

In this facility there is no control of the gas bubbles and these appear as traveling bubbles as the pressure in the test section decreases at high velocity. As the flow velocity increases, sheet cavitation inception starts occurring on the wedge at around $V_{\text{inlet}} = 5.9$ m/s, which corresponds to $\sigma \sim 6.7$. Figure 4 shows a sample image of the flow at $V_{\text{inlet}} = 7.6$ m/s, in which a steady small cavity (length $\sim 0.3"$) can be observed. The leading edge of the cavity is located at the beginning of the throat section.

As the inlet velocity increases or the cavitation number decreases, the cavity length increases. The leading edge of the cavity remains steady while vortices are shed from the trailing edge of the cavity. At such a relatively low flow rate, break-up of the cavity is not observed.

**Figure 2:** Relationship between the inlet pressure and the inlet flow velocity.

**Figure 3:** Variations of the cavitation number with the inlet flow velocity.

**Figure 4:** Sample image of flow visualization near cavitation inception, $V_{\text{inlet}} = 7.6$ m/s ($\sigma$~4).

This type of vortex shedding from the trailing edge of the cavity is dominant for $V_{\text{inlet}} \leq 9$ m/s. Under these flow conditions, it is not clear if a reentrant jet forms since it is not strong enough to reach the leading edge of the cavity to break it into two. A sequence of images with 0.5 ms intervals for $V_{\text{inlet}} = 8.4$ m/s is shown in Figure 5. The trailing edge of the cavity grows, breaks off, and dissipates into a cloud of fine bubbles. The maximum length of the sheet cavity...
increases with $V_{\text{inlet}}$, with the sheet regularly interrupted into vortex shedding. This vortex shedding repeats regularly at a relatively high frequency with no merging of the shed vortices observed.

**REENTRANT JET DOMINANT SHEET-CLOUD CAVITATION FLOW**

As the velocity increases further, the reentrant jet becomes stronger and reaches the edge of the cavity to break it completely. The cycle evolves as described in De Lange et al., 1994:

- a cavity grows,
- a reentrant jet forms at the trailing edge,
- the reentrant jet moving upward towards to the leading edge,
- the reentrant jet reaches the leading edge of the cavity and breaks the cavity,
- a new cycle starts and the above process continue.

![Figure 5: A sequence of images 0.5 ms apart showing vortex cloud shedding at the trailing edge of the cavity and a steady cavity in the leading edge. $V_{\text{inlet}} = 8.4$ m/s ($\sigma$=3.6).](image)

Figure 6 shows the growth of a new cavity behind the bubble cloud from the previous cavity (Figure 6a). As the sheet cavity grows, a portion of the cavity near the leading edge becomes clear (Figure 6b), the size of glass cavity portion also increases as the cavity grows (Figure 6c-f). A reentrant jet forms and starts to move toward the leading edge of the cavity, as pointed by the blue arrows in Figure 6d to Figure 6f.

![Figure 6: A sequence of images 2 ms apart showing the development of the sheet cavity. $V_{\text{inlet}} = 9.8$ m/s ($\sigma$=3.1).](image)

If the reentrant jet is strong enough, it can advance upstream further toward the leading edge of the cavity and can completely break the cavity. Figure 7 shows a time sequence of such a process. As the reentrant jet moves up, the size of the clear portion of the cavity near the leading edge of the cavity shrinks while the overall cavity still grows, as shown in Figure 7a through Figure 7f. After the reentrant jet hits the leading edge of the cavity, a large portion of the cavity detaches from the edge of the profile and becomes a bubble cloud, as shown in Figure 7i. As the bubble cloud moves downstream, a new sheet cavity is formed and starts to grow, as shown in Figure 7g - Figure 7i.

As the large separated bubble cloud moves downstream, it further breaks down into smaller bubble clouds of various sizes with the vortical cloud downstream moving faster than the ones ahead. The vortices merge into larger ones as they move downstream. Figure 8 illustrates this process of the breaking of a large bubble cloud into smaller vortices and the merging of the vortices into a larger vortex structure of bubble clouds.
Figure 7: A sequence of images 0.75 ms apart showing the development of a reentrant jet and break of the cavity. \( V_{\text{inlet}} = 9.8 \text{ m/s (} \sigma \approx 3.1 \).}

DEVELOPMENT OF A TWO-PHASE SHOCK

As the inlet flow velocity further increases, especially for flows with \( V_{\text{inlet}} \geq 13 \text{ m/s} \), the sheet cavity collapse becomes driven by a two-phase flow shock wave. Under these flow conditions, the local liquid speed exceeds the sound speed in the two-phase medium and a shock develops. A relatively high downstream pressure initiates the shock front at the trailing edge of the cavity and the shock then moves upstream towards the wedge leading edge (see Figure 9). The velocity of the shock is much faster than that of the reentrant jet.

The shock overtakes the jet easily, and collapses the sheet cavity enabling a new cycle to start with the formation of a new sheet cavity. The traveling gas bubbles in the free stream above the sheet cavity, which are visible before the shock passage, disappear completely as the shock passes by indicating that the shock location extends beyond the sheet cavity.

Figure 9 shows a time sequence of such a process at \( V_{\text{inlet}} = 14.25 \text{ m/s} \). Under this relatively high flow velocity and low local pressure, nuclei in the free stream above the sheet cavity grow and are visible before shock wave formation, as seen in Figure 9a. More difficult to see in Figure 9a is a reentrant jet, which moves upstream toward the leading edge of the cavity. A shock then forms and moves very fast upstream. A slant shock front, indicated by red arrows, can be observed in Figure 9b through Figure 9g progressing fast toward the leading edge of the cavity. Once the shock wave reaches the leading edge of the cavity, the cavity breaks into a bubble cloud, which detaches from the wedge and moves downstream, as shown in Figure 10a.

Distinct bubble cloud vortices can be observed even before the shock front reaches the leading edge of the cavity, as evident in Figure 9g. These bubble vortices grow and merge as they move downstream as shown in Figure 10a to Figure 10c. A new sheet cavity is then initiated and starts to grow, as shown in Figure 10b through Figure 10c.

Figure 8: A sequence of images 1.5 ms apart showing the formation and merging of multiple vortices from the detached cavity. \( V_{\text{inlet}} = 9.8 \text{ m/s (} \sigma \approx 3.1 \).}

The evolution of the sheet cavity edge with time can be obtained by analyzing the high-speed photography images. This provides the dynamics of the sheet cavity development. Figure 11 shows the boundary evolution of the sheet cavity for \( V_{\text{inlet}} = 14.0 \text{ m/s} \). This plot gives a clear indication of how the cavity length, \( L \), (measured from the beginning
of the throat), the cavity height, \( H \), (measured as the maximum difference in vertical direction of the cavity boundary) and the geometric height of the bottom profile covered by the sheet cavity, \( h \), change as the sheet cavity develops. Figure 12 shows the evolution of the cavity boundary as the shock moves toward the leading edge of the cavity, the image analysis becomes less accurate as the shock front moves toward the leading edge. The eye can follow better the shock front evolution as in Figure 9.

Figure 15 shows the evolution of the reentrant jet speed as a function of the distance to the wedge leading edge at \( V_{inlet} = 14.0 \) m/s. Overall, the velocity of the reentrant jet is relatively slow but accelerates as the jet moves toward the leading edge of the cavity.

Figure 12: Evolution of the cavity boundary of a cavity with a developing shock front, red arrows indicate the shock front detected from image analysis. \( V_{inlet} = 14 \) m/s. (\( \sigma \sim 2.7 \)).

Figure 10: A sequence of images 3.69 ms apart showing the collapse of the cavity after the passing of the shock shown in Figure 9. \( V_{inlet} = 14.25 \) m/s. (\( \sigma \sim 2.7 \)).
The measured speed of the shock front is an order of magnitude faster than the reentrant jet speed. This is shown in the Figure 16. This shock speed increases as the shock approaches the leading edge of the cavity, changing from around 20 m/s downstream to above 40 m/s near the throat. Since the sound speed in a bubbly mixture with void fractions between 0.3 and 0.7 is about 20 m/s (Brennen, 1995), the local Mach number is close to 2.

**Figure 13:** Variations of the height of the trailing edge of growing sheet cavities with the sheet cavity length at $V_{inlet} = 14$ m/s ($\sigma$~2.7). The definitions of the height and length of the cavity are shown in Figure 11.

**Figure 14:** Variations of velocity of the trailing edge of growing sheet cavities with the sheet cavity length at $V_{inlet} = 14$ m/s ($\sigma$~2.7). The definitions of the length of the cavity are shown in Figure 11.

**Figure 15:** Velocity variations of developing reentrant jets with the distance from leading edge of the cavity ($x = 0$) for $V_{inlet} = 14$ m/s ($\sigma$~2.7).

**Figure 16:** Velocity variations of shock front with the distance from leading edge of the cavity ($x = 0$) for $V_{inlet} = 14$ m/s ($\sigma$~2.7).

**Figure 17:** A sequence of representative events of a sheet-cloud cavitation flow. $V_{inlet} = 14$ m/s ($\sigma$~2.7).
Figure 18: Pressure signals measured at locations T1, T2, and T3 covering two successive shock events. The alphabetic markings correspond to the same marking of images in Figure 17.

PRESSURE MEASUREMENTS

The pressures were measured at the same time and were synchronized with the high-speed movie sequences. The data was then analyzed to examine the correlations between the cavity dynamics and the pressure variations. The pressure signals were obtained at T1, T2, and T3, corresponding to the locations where the three flush pressure transducers were placed (see Figure 1). Figure 17 shows an image sequence of representative events excerpted from a high-speed movie taken at $V_{\text{inlet}} = 14.0$ m/s, where a two-phase shock front progression was observed. Figure 18 shows the corresponding pressure signals for two successive shock passages. The alphabetic marking in Figure 18 indicates the time corresponding to the image with the same alphabetic number in Figure 17.

Figure 17a through Figure 17c show the developing sheet cavity when it reaches gauges T1 to T3 respectively. In Figure 17c a clear sheet cavity has formed near the leading edge of the sheet cavity. The pressure signals in Figure 18 indicate that the pressure drops close to the vapor pressure as the cavity reaches each of the transducers (red, then green, then blue traces).

Figure 17d to Figure 17f show the upstream advance of a reentrant jet: a dense bubbly mixture moves upstream from the trailing edge to the leading edge of the cavity, the front of which can be clearly seen in the images. The clear cavity volume shrinks as the reentrant jet moves upstream. However, this does not result in any significant pressure changes at the wall as shown in Figure 18 at the corresponding (d) to (f) times.

As the reentrant jet reaches the cavity leading edge, a shock wave appears in the left hand of the field of view and is then seen moving fast upstream. Figure 17g and Figure 17h show the moments right before and after the shock passes over transducer T3. A pressure surge is clearly detected by T3 (blue trace in Figure 18 at 732 ms).

Figure 17i shows the shock passing over T2 followed in Figure 17j by the complete collapse of the sheet cavity on T1. As a result we see a pressure spike followed by a longer duration pressure increase due to the longer duration collapse of the cavity and following cloud. Figure 17i and Figure 17j also show a bubble cloud breaking from the sheet cavity and forming large vortical structures that tumble downstream, as the shock moves upstream.

With the wedge free of cavities, a new sheet cavity initiates, as shown in Figure 17k. As the new sheet cavity grows further, as shown in Figure 17l, the pressure transducer at T1 is fully covered by the cavity and the pressure drops back to almost vapor pressure at T1, while high pressure fluctuations are still present at T2 and T3 due to cloud cavitation activity from the previous event.

The sudden large rise of the pressure observed in Figure 18 (as high as 100 psi!) corresponds to the shock passing over the transducer. The shock reaches T3 (blue) first, then T2 (green), and last T1 (red). T1, which is near the leading edge of the sheet cavity, sees the highest amplitude and shortest duration spike due to the fact that a new sheet cavity forms right after the shock passage and covers T1, dropping the pressure to almost vapor pressure. For the other transducers further downstream, the pressure drops at a much later time when the new sheet cavity reaches it and covers it. One
can observe multiple large pressure fluctuations at T3 before the pressure fluctuations become quiet due to the passage of large vortical structures moving downstream (see Figure 19).

**Figure 19:** Formation and passage of large vortical structures following the show collapse of the cavity.

**EFFECTS OF INLET VELOCITY ON SHEET-CLOUD CAVITATION FLOW**

As discussed earlier, sheet cavity behavior changes significantly with the inlet velocity. Using the cavity length defined in Figure 11, high speed movies at different \( V_{inlet} \) were analyzed to measure the maximum length a sheet cavity reaches before it breaks off. At least 30 events were used in the measurements. The averaged sheet cavity length, \( L_{avg} \), the maximum cavity length, \( L_{max} \), and the minimum cavity length, \( L_{min} \), were obtained at different \( V_{inlet} \), using the repeated measurements. The top plot in Figure 20 shows \( L_{avg} \) as a function of \( V_{inlet} \). Interestingly, this length increases almost linearly with the inlet velocity. When comparing \( L_{max}/L_{avg} \) and \( L_{min}/L_{avg} \) as functions of \( V_{inlet} \), as shown in the bottom of Figure 20, the differences between the minimum and maximum lengths become larger as the inlet flow velocity increases, i.e. the scatter increases as the inlet velocities increases.

The growth period of the cavity, i.e. the time duration from cavity inception to reaching maximum cavity length, \( \Delta t \), also depends strongly on the inlet flow velocity. Figure 21 shows the variation of the corresponding non-dimensional time duration, defined as \( \Delta t/(L_{avg}/V_{inlet}) \), with the inlet flow velocity. The normalized time duration is much larger at low inlet velocities and drops to almost a constant ~ 2 when the inlet flow velocity increases to above 9 m/s. The corresponding non-dimensional growth velocity of the trailing edge of a developing cavity as a function of the inlet velocity is shown in Figure 22. The developing speed increases significantly as the inlet flow velocity increases until it reaches a plateau for inlet flow velocities higher than 10 m/s.

**Figure 20:** Variations of the average cavity length (top) and the ratios of maximum and minimum cavity lengths over the average cavity length (bottom) with inlet flow velocity.

**Figure 21:** Variations with the inlet velocity of the normalized period of a cavity in its development phase.

**Figure 22:** Variations with the inlet velocity of the normalized speed of the trailing edge of a cavity in its development phase.
Figure 23 shows a few examples of the auto-correlation values for different inlet flow velocities and at the different locations. Distinctively repeating flow structures are seen to not exist until the flow speed exceeds 9 m/s. Above that speed regularly recurring flow structures are present. As clearly seen from Figure 24, the frequency of recurrence decreases with increasing inlet velocity and then reaches a plateau for velocities above 10 m/s. The figure shows the frequency of the peak correlation deduced from Figure 23 and the corresponding Strouhal number as functions of the inlet velocity. In addition to the low frequency high amplitude fluctuations due to large flow structures development, there are also high frequency fluctuation components more prominent in the upstream location, which correspond to small flow structures riding on the large flow structures. The bottom graph in Figure 24 shows the variation of two Strouhal numbers, defined as $St_L = fL_{avg}/V_{inlet}$ when using as characteristic length the average sheet cavity length, $L_{avg}$, and $St_H = fH_{inlet}/V_{inlet}$ when using the inlet height of the test section. Both Strouhal numbers converges to the same value as the inlet flow velocity exceeds 8 m/s.

CAVITATION INDUCED PRESSURE

As described previously, the sheet to cloud cavitation phenomenon results in significant local pressure fluctuations. Figure 25 shows an example of the pressure signals at the four pressure gauges T1 through T4 when the sheet cavity has a reentrant jet dominated dynamics at $V_{inlet}=14.0$ m/s. Figure 26 is a zoom of the same pressure signals. Compared with the pressure signals obtained in the shock dominated cases, as shown in Figure 18, the signal amplitude is much lower and the periods are much shorter.

Comparing the pressure signals between the four locations in Figure 26, we can see that the pressure at T4 contains both stronger positive and stronger negative pressure peaks with a wider duration of the positive pressure. The durations of the positive pressure shorten as the measurement location is closer to the throat. This could be attributed to the fact that closer to the leading edge of the cavity, the transducer is covered by sheet cavities for a longer period of time.

One way to characterize the pressure variations of the sheet-cloud cavitation is to compute the time duration, $\Delta t$, over which the local pressure is higher than a given threshold pressure, $P_t$. We can define a non-dimensional parameter, $\Delta t/T$, where $T$ is the total time duration of the observation. $\Delta t/T$ gives the percentage of the total time during which the pressure is above $P_t$.

Figure 23: Variations of the auto-correlation values of the acoustic pressures for different inlet velocities and at three transducer locations.

Auto-correlation of the acoustic signal was performed for different inlet flow velocities to examine the resemblance of the pressures due to the recurring flow structures in the sheet-cloud cavitation events.
Figure 24: Frequency of recurrence of sheet cavity structures and corresponding Strouhal numbers versus the inlet velocity, $V_{\text{inlet}}$.

Figure 25: Time variation of acoustic pressures at different locations, $V_{\text{inlet}} = 14 \text{ m/s}$.

Figure 26: Zoom on a portion of the pressure signals shown in Figure 25.

Figure 27: Variation of impact time duration with pressure threshold at various flow velocities at different locations.
For example, as the velocity increases of \( t \) becomes higher again after the flow becomes shock dominated, i.e. \( V_{inlet} > 12 \) m/s. The opposite trend is seen at locations T2 and T3, i.e. there is a crossover at around \( V_{inlet} = 12 \) m/s, with \( P_t \) being observed at T1 instead of T2 and T3. At the downstream location T4, the normalized threshold is seen to be overall the highest almost all inlet flow conditions after \( V_{inlet} > 9 \) m/s. All these variations are related to the cavity development and subsequent vortex shedding. Figure 29 shows the variation of the normalized peak pressure duration, \( \Delta t / T \), with \( V_{inlet} \) for a fixed pressure threshold \( P_t = 0.5 \rho V_{inlet}^2 \). We see that downstream T4 measures the largest \( \Delta t / T \), especially when the flow corresponds to shock wave generation.

**SUMMARY**

A convergent-divergent test section was used to study sheet to cloud cavitation experimentally. Flow visualizations and pressure measurements were obtained for different flow regimes as the inlet flow velocity was increased. As the velocity increases, the regime changes from being dominated by vortex shedding, to being dominated by reentrant jet formation, and then by two-phase shock formation. When a shock forms, the shock front moves much faster toward upstream than the reentrant jet does. The measured shock velocities are an order of magnitude higher that the reentrant jet velocities and exceed the local sound speed. The shock fronts generate clear shock-like pressure traces while crossing a pressure measurement station. Sheet to cloud cavitation reaches a stable periodic state once the inlet velocity is above certain threshold value (about 9 m/s for this test section). The corresponding frequency of recurrence of the sheet cavity decreases when the inlet flow velocity increases, and the corresponding Strouhal number decreases even more. However, the decrease of the Strouhal number becomes small once the flow reaches the shock dominated regime. During reentrant jet and shock dominated flow regimes, bubble clouds break off from the sheet cavity and form large vortical structures. These bubble clouds can also create relatively high pressure fluctuations as they move downstream with the flow.

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