An experimental study of sheet to cloud cavitation
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A B S T R A C T
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.

1. 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 [3,5].

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 [9,19,15,18,20,12,4]. By blocking the reentrant jet with an obstacle, the periodic shedding could be prevented [14]. Adverse pressure plays an important role in the formation of the reentrant jets [4,11,16].

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 [7,1,2,13,18]. Then, the periodic shedding could be affected or prevented from occurring [8,16].

Measurements of the void fractions in the cavity and the clouds have been attempted [22,23,21,6]. 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 et al. [10]. 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.

2. Experimental setup
A sketch of the test section with the main dimensions is shown in Fig. 1 and a sketch of the overall setup is shown in Fig. 2. The flow passage in the acrylic test section is formed using profiled top and bottom inserts sandwiched between two side walls 2.22 cm apart to enable good visualization. The inlet and outlet sections have the same dimensions: height 10.16 cm and width 2.22 cm. When designing the convergent-divergent a small flat region 2.54 cm 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 36 L/s at 180 kPa. 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.

3. Inlet pressure and cavitation number

The inlet pressure, \(P_{\text{inlet}}\), plotted versus the inlet flow velocity, \(V_{\text{inlet}}\), is shown in Fig. 3. 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. Fig. 4 shows the corresponding cavitation number,

\[
\sigma = \frac{(P_{\text{inlet}} - P_v)}{0.5 \rho V_{\text{inlet}}^2}
\]

4. 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 \(\sigma \sim 6.7\). Fig. 5 shows a sample image of the flow at \(V_{\text{inlet}} = 7.6\) m/s, in which a steady small cavity (length \(\sim 7.6\) mm) 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.

This type of vortex shedding from the trailing edge of the cavity is dominant for \( V_{\text{inlet}} \leq 9 \text{ m/s} \). 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 \( V_{\text{inlet}} = 8.4 \text{ m/s} \) is shown in Fig. 6. 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.

5. 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 [17]:

- a cavity grows,
- a reentrant jet forms at the trailing edge,
- the reentrant jet moving upward towards 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.

Fig. 7 shows the growth of a new cavity behind the bubble cloud from the previous cavity (Fig. 7a). As the sheet cavity grows, a portion of the cavity near the leading edge becomes clear (Fig. 7b), the size of glass cavity portion also increases as the cavity grows (Fig. 7c–f). A reentrant jet forms and starts to move toward the leading edge of the cavity, as pointed by the blue1 arrows in Fig. 7d to f.

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. Fig. 8 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 Fig. 8a through f. 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 Fig. 8i. As the bubble cloud moves downstream, a new sheet cavity is formed and starts to grow, as shown in Fig. 8g-i.

\footnote{1 For interpretation of color in Figs. 7, 10, and 19, the reader is referred to the web version of this article}
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. Fig. 9 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.

6. 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 initiate the shock front at the trailing edge of the cavity and the shock then moves upstream towards the wedge leading edge (see Fig. 10). 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.

Fig. 10 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 Fig. 10a. More difficult to see in Fig. 10a is a reentrant jet, which moves upstream toward the leading edge of the cavity. A slant shock front, indicated by red arrows, can be observed in Fig. 10b through g 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 Fig. 11a.

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Distinct bubble cloud vortices can be observed even before the shock front reaches the leading edge of the cavity, as evident in Fig. 10g. These bubble vortices grow and merge as they move downstream as shown in Fig. 11a to c. A new sheet cavity is then initiated and starts to grow, as shown in Fig. 11b through c.

The evolution of the sheet cavity edge with time can be obtained by analyzing the high-speed photography images. A sequence of images is extracted from the movies with known time separation between them. These are then analyzed using image software such as ImageJ from NIH. The images are enhanced, the background subtracted, and then edge detection of the boundaries of the sheet cavity is executed. From these contours and the times the quantities shown below are extracted and plotted. This provides the dynamics of the sheet cavity.
cavity development. Fig. 12 shows the boundary evolution of the sheet cavity for $V_{\text{inlet}} = 14.0$ 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. Fig. 13 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 Fig. 10.

Fig. 14 shows variations of the cavity height with the cavity length for growing sheet cavities at $V_{\text{inlet}} = 14$ m/s. It shows clearly that the cavity height changes almost linearly with the cavity length except for the very short cavities, where the cavity height remains the same while the length increases. Fig. 15 shows the variation of the trailing edge velocity of the developing cavities as the cavity length changes. Although the velocity varies significantly, especially in the early development stage when the cavity length is short (near the wedge leading edge), the cavity trailing edge velocity increases slightly as the cavity length $L$ increases and is overall slower than the inlet liquid velocity (of the order of 1/3 in this figure).

Fig. 16 shows the evolution of the reentrant jet speed as a function of the distance to the wedge leading edge at $V_{\text{inlet}} = 14.0$ 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.

The measured speed of the shock front is an order of magnitude faster than the reentrant jet speed. This is shown in Fig. 17. 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 [3], the local Mach number is close to 2.

7. 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 Fig. 2). Fig. 18 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. Fig. 19 shows the corresponding pressure signals for two successive shock passages. The alphabetic marking in Fig. 19 indicates the time corresponding to the image with the same alphabetic number in Fig. 18.

Fig. 18a through c shows the developing sheet cavity when it reaches gauges T1 to T3 respectively. In Fig. 18c a clear sheet cavity has formed near the leading edge of the sheet cavity. The pressure signals in Fig. 19 indicate that the pressure drops close to the vapor pressure as the cavity reaches each of the transducers (red, then green, then blue traces).

Fig. 18d to f shows 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 sig-
significant pressure changes at the wall as shown in Fig. 19 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

Fig. 12. Evolution of the cavity boundary of a developing sheet cavity. \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)).

Fig. 13. Evolution of the cavity boundary of a cavity with a developing shock front, red arrows indicate the shock front detected from image analysis. \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 14. Variations of the height of the trailing edge of growing sheet cavities with the sheet cavity length at \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)). The definitions of the height and length of the cavity are shown in Fig. 12. The dashed line indicates the height of the profile of the bottom insert, other symbols of different colors indicate repeats of the observations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 15. Variations of velocity of the trailing edge of growing sheet cavities with the sheet cavity length at \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)). The definitions of the length of the cavity are shown in Fig. 12. Symbols of different color indicate different sheet cavities studied. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 16. Velocity variations of developing reentrant jets with the distance from leading edge of the cavity (\( x = 0 \)) for \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)). Symbols of different color indicate different sheet cavities studied. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 17. Velocity variations of shock front with the distance from leading edge of the cavity (\( x = 0 \)) for \( V_{\text{inlet}} = 14 \text{ m/s} \) (\( \sigma \sim 2.7 \)).
seen moving fast upstream. Fig. 18g and h show the moments right before and after the shock passes over transducer T3. A pressure surge is clearly detected by T3 (blue trace in Fig. 19 at 732 ms).

Fig. 18i shows the shock passing over T2 followed in Fig. 18j 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. Fig. 18i and j also show a bubble cloud breaking from the sheet cavity and forming large vortical structures that tumble downstream, as the shock moves upstream.

Fig. 18. A sequence of representative events of a sheet-cloud cavitation flow. $V_{\text{inlet}} = 14$ m/s ($\sigma = 2.7$).

With the wedge free of cavities, a new sheet cavity initiates, as shown in Fig. 18k. As the new sheet cavity grows further, as shown in Fig. 18l, 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 Fig. 19 (as high as 690 kPa!) 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 Fig. 20).

8. 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 Fig. 12, high speed movies at different $V_{\text{inlet}}$ 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, $L_{\text{avg}}$, the maximum
cavity length, $L_{\text{max}}$, and the minimum cavity length, $L_{\text{min}}$, were obtained at different $V_{\text{inlet}}$, using the repeated measurements. The top plot in Fig. 21 shows $L_{\text{avg}}$ as a function of $V_{\text{inlet}}$. Interestingly, this length increases almost linearly with the inlet velocity. When comparing $L_{\text{max}}/L_{\text{avg}}$ and $L_{\text{min}}/L_{\text{avg}}$ as functions of $V_{\text{inlet}}$, as shown in the bottom of Fig. 21, 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.

Fig. 19. 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 Fig. 18.

Fig. 20. Formation and passage of large vortical structures following the shock collapse of the cavity.

Fig. 19. 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 Fig. 18.

Fig. 21. Variations of the average cavity length and ratios of maximum and minimum cavity lengths over the average cavity length with inlet flow velocity.

Fig. 20. Formation and passage of large vortical structures following the shock collapse of the cavity.

Fig. 21. Variations of the average cavity length and ratios of maximum and minimum cavity lengths over the average cavity length with inlet flow velocity.

Fig. 22. Variations with the inlet velocity of the normalized period of a cavity in its development phase.

Fig. 22. Variations with the inlet velocity of the normalized period of a cavity in its development phase.
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. Fig. 22 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 $\approx 2$ 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 Fig. 23. 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.

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. Fig. 24 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 Fig. 25, 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 Fig. 25 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 Fig. 25 shows the variation of two Strouhal numbers, defined as $St_1 = f_{avg}/V_{inlet}$ when using as characteristic length the average sheet cavity length, $L_{avg}$, and $St_2 = fH_{inlet}/V_{inlet}$ when using the inlet height of the test section. Both Strouhal numbers converge to the same value as the inlet flow velocity exceeds 8 m/s.

9. Cavitation induced pressures

As described previously, the sheet to cloud cavitation phenomenon results in significant local pressure fluctuations.
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, $D = \frac{T}{\Delta t}$, where $T$ is the total time duration of the observation. $D = \frac{T}{\Delta t}$ gives the percentage of the total time during which the pressure is above $P_t$.

Fig. 28 shows the variation of $\Delta t$ with $P_t$ at the three transducers for different inlet flow velocities. For low $V_{inlet}$ where the cavitation is mainly at the wedge leading edge, i.e. near T1, a higher $P_t$ is measured for a given $\Delta t$ (or a longer duration is observed for a given $P_t$). However, the highest $P_t$ is relatively low in all these cases (less than 6.9 kPa).

As the flow changes from vortex shedding to a reentrant jet dominated regime (e.g. $V_{inlet} = 11.2$ m/s), the sheet cavity grows, the downstream locations (T2 and T3) start to have larger $\Delta t$ and higher maximum $P_t$ than the upstream region, T1. At even higher inlet flow velocity (e.g. $V_{inlet} = 14$ m/s), the flow becomes shock dominant. Even though the overall shape still looks similar to those at lower inlet velocity cases, i.e. impact durations are longer at lower $P_t$, $D = \frac{T}{\Delta t}$ can now be larger in the upstream region (T1) at higher $P_t$. For example, $\Delta t$ at the highest $P_t$ is obtained at T1 as shown in the case of $V_{inlet} = 14$ m/s in Fig. 28.

Fig. 29 shows the variation of the normalized peak pressure, $P_t/0.5\rho V_{inlet}^2$, with $V_{inlet}$ for a fixed normalized peak duration, $\Delta t/T$, of 0.01%. The normalized pressure threshold at the upstream location T1 has the highest value at the lower inlet velocities, $V_{inlet} < 7$ m/s. It 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.

Fig. 30 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.
Fig. 28. Variation of impact time duration with pressure threshold at various flow velocities at different locations.

Fig. 29. Normalized pressure threshold, $P_t/0.5\rho V_{\text{inlet}}^2$, as a function of $V_{\text{inlet}}$ for a selected normalized peak duration, $\Delta t/T$, 0.01%.

Fig. 30. Normalized duration $\Delta t/T$ as a function of $V_{\text{inlet}}$ at threshold pressure $P_t = 0.5\rho V_{\text{inlet}}^2$. 
Conclusions

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 than 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 a 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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