Effect of Non-Condensable Gas Injection on Cavitation Dynamics of Partial Cavities

Simo A. Mäkiharju, Harish Ganesh, and Steven L. Ceccio
University of Michigan, Ann Arbor, MI 48109, USA
E-mail: smakihar@umich.edu

Abstract. Partial cavities can undergo auto-oscillation causing large pressure pulsations, unsteady loading of machinery and generate significant noise. In the current experiments fully shedding cavities forming in the separated flow region downstream of a wedge were investigated. The Reynolds number based on hydraulic diameter was of the order of one million. The cavity dynamics were studied with and without injection of non-condensable gas into the cavity. Gas was injected directly into the cavitation region downstream of the wedge's apex, or into the recirculating region at mid cavity so that for the same amount of injected gas less ended up in the shear layer. It was found that relatively miniscule amounts of gas introduced into the shear layer at the cavity interface can reduce vapour production and dampen the auto oscillations, and the same amount of gas injected into the mid cavity would not have the same effect. The authors also examined whether the injected gas can switch the shedding mechanism from one dominated by condensation shock to one dominantly by re-entrant jet.

1. Introduction

Partial cavitation occurs in numerous industrial and naval applications. Cavitation on lifting surfaces or in cryogenic rocket motors can damage equipment, and in general be detrimental to the system performance. Much work has gone into understanding the basic physical processes involved [2, 3, 4, 8]. If a partially cavitating condition is likely to occur, it would be of use to be able to control it. Kawanami et al. [6] used obstacles to prevent a re-entrant from moving upstream and they were successful in preventing the generation of cloud cavitation. However, recently Ganesh et al. [5] discovered that under certain conditions a condensation shock can be the dominant mechanism instead of a re-entrant jet, and under these conditions an obstacle placed on the surface is not sufficient to prevent cloud shedding from partial cavities.

To investigate the nature of cloud shedding in conditions where a condensation shock occurs, we investigated the effect of non-condensable gas injection both from the apex and into the mid cavity.

2. Experimental setup

Experiments were carried out at the University of Michigan 9-Inch Water Tunnel. We utilized the X-ray densitometry system described by Mäkiharju et al. [7] to measure the time resolved 2D void fraction distribution without flow perturbations. To reduce the baseline attenuation, the water tunnel’s test section was further contracted to have a (76mm)^2 cross-section.

The wedge geometry and gas injection locations are shown in figure 1. In addition to the 1 kHz void fraction measurements, the unsteady pressure was measured using surface mounted transducers sampled at 500 kHz. The transducers were located at 32 and 50 mm downstream of the apex.
Figure 1. Schematic of the experimental setup. The red arrows indicate the apex and mid cavity gas injection locations, which were ~25mm apart in the streamwise direction.

3. Shedding partial cavitation

The cavitation regime changes as a function of the cavitation number defined as

$$\sigma_\infty = \frac{p_\infty - p_v}{\frac{1}{2} \rho U^2}$$

For the present study the free stream speed, $U$, was fixed at $8 \pm 0.1$ m/s and the inlet pressure kept constant at $p_\infty = 63.5 \pm 1$ kPa. Hence, the cavitation number was fixed at $\sigma_\infty = 1.9 \pm 0.1$. For the geometry and flow conditions chosen, propagation of bubbly shock waves leads to the partial cavity shedding, as shown in figure 2. In the cavity the average void fraction was $\bar{\alpha}_{MAX} \sim 40\%$.

Figure 2. Side view of the shedding cavity as viewed in (a) visible light. In (b) and (c) we see a 2D X-ray projection of the void fraction distribution. In (c) a condensation shock is seen moving upstream.
4. Effect of gas injection

For the present flow we expect most of the vapour to be created in the shear layer. Our hypothesis is that i) introduction of non-condensable gas into the shear layer would predominantly reduce the amount of vapor created per cycle, as the presence of the gas will increase pressure in the shear layer’s vortex cores and possibly increase suction peak pressure. And, ii) introduction of non-condensable gas into the mid cavity would predominantly change the condensation shock speed, as a condensation shock in two phase mixture could be expected to propagate at speed \( u \) given by

\[
    u^2 = \frac{p_2 - p_1}{\rho} \left( \frac{1}{1 - \alpha_2} \right)
\]

This is further discussed in Brennen [1], and the above equation is the result of ignoring the bubble dynamics. Here the sub-indices 1 and 2 denote conditions up- and downstream of the shock, respectively. From this we can see if both \( \alpha_1 \) and \( \alpha_2 \) increase equally, the shock speed would increase, and if \( p_2 - p_1 \) decreases, the shock speed decreases.

To determine what constitutes a significant amount of gas injection, we first estimated the vapour production rate by cavitation based on the void fraction measurements obtained using X-ray densitometry. The normalized vapour production rate was defined as

\[
    q_C = \frac{Q}{UL_{cav}b},
\]

where \( Q \) is volume flux of vapour at cavity pressure, \( L_{cav} \) is cavity length and \( b \) is the span. The value of \( C_q \) for the present setup and \( \sigma_\infty = 1.9 \) was found to be \( \mathcal{O}(10^{-2}) \), similar to that of Stutz and Rebound [8] who found \( C_q \sim 0.006 \). The normalized amount of injected gas was defined similarly as \( q_I C \).

Figure 3 shows the unsteady pressure signal and their FFTs without and with gas injection. Without gas injection we observe strong shedding at \( St \sim 0.27 \), where the Strouhal number is defined as

\[
    St = \frac{fL_{cav}}{U}.
\]

However, with injection of a relatively small amount of gas from the apex (\( C_q / q_C \sim 0.3 \)) the shedding cycle became more weakly periodic, average void fraction was reduced, as seen in figure 4, and cavity begins to be reminiscent of a transitional cavity, as discussed in [5]. Figure 4 also shows that injecting the same amount of gas into the mid cavity, has almost no observable effect. This would be consistent with suppression of vapour generation in the shear layer (i.e. the first hypothesis).

![Figure 3. Pressure signals and their FFTs without (left) and with (right) gas injection from the apex at a rate of \( C_q / q_C \sim 0.3 \). The top and middle figures show the pressure signals 32 and 50 mm downstream of the apex, respectively. The bottom figures show the FFTs of these signals.](image)
5. Discussion and conclusions

Injection of even a relatively small amounts ($C_{qI}/C_q \sim 0.3$) of non-condensable gas into the shear layer (i.e. from the apex) can dampen the shedding cycle by significantly reducing the vaporization rate of the liquid. Injecting the same amount of non-condensable gas into the mid cavity had a much weaker overall effect than injection from the apex. The authors are currently conducting additional experiments to further study effect of increased gas injection (up to $C_{qI}/C_q \sim 4$), as well as to better quantify the change in shock speed and void fraction.

Acknowledgements

This work was supported by the Office of Naval Research Grant N00014-14-1-0292, under program manager Dr. Ki-Han Kim.

References

[1] Brennen, C. E. Fundamentals of Multiphase Flows, Cambridge University Press, 2005
[2] Callenaere, M., Franc, J-P., Michel, J-M. & Riondet, M., “The cavitation instability induced by the development of a re-entrant jet”, J. Fluid Mech. 444, 223-256, 2001
[3] Coutier-Delgosha, O., Devillers, J.-F., and Pichon, T., “Internal structure and dynamics of sheet cavitation”, Phys. Fluids, 18, No. 017103, 1-12, 2006
[4] Coutier-Delgosha, O., Stutz, B., Vabre, V. & Legoupil, S., “Analysis of cavitating flow structure by experimental and numerical investigations”, J. Fluid Mech. 578, 171-222, 2007
[5] Ganesh, H., Mäkiharju, S.A., and Ceccio, S.L. "Bubbly shock propagation as a mechanism for sheet-to-cloud transition of partial cavities.” Submitted to the Journal of Fluid Mechanics.
[6] Kawanami, Y., Kato, H., Yamaguchi, H., Tanimura, M. & Tagaya, Y., “Mechanism and control of cloud cavitation”, Trans. ASME: J. Fluids Engng. 119, 788-795, 1997
[7] Mäkiharju, S.A., Chang, N., Gabillet, C., Paik, B-G., Perlin, M. & Ceccio, S.L., “Time Resolved Two-dimensional X-Ray Densitometry of a Two Phase Flow Downstream of a Ventilated Cavity”, Experiments in Fluids, 54, 2013
[8] Stutz, B., and Reboud, J. L. “Experiments on unsteady cavitation.” Exp. in Fluids, 22(3), 1997