

# Investigation of the effects of air injection on the unsteady sheet/cloud cavity behaviors

C C Wang, G Y Wang\* and B Huang

School of Mechanical Engineering, Beijing Institute of Technology, Beijing, China

wanguoyu@bit.edu.cn

**Abstract.** The objective of this paper is to investigate the effect of air injection on unsteady sheet/cloud cavity behaviors. Experiments are conducted in the divergent section with a ventilation slit downstream the throat of a convergent-divergent channel, using high-speed camera to visualize the transient cavity behaviors. Results are presented for the sheet/cloud cavitation characterized by the periodic large-scale cavity cloud being shed at a cavitation number of  $\sigma=0.8$  and the Reynold number of  $Re=0.97\times10^6$ , for three normalized air injection volume flow rates, namely  $C_f=0$ ,  $1.135\times10^{-3}$  and  $2.270\times10^{-3}$ . The results show that air injection can significantly influence the unsteady sheet/cloud cavity behaviors. With the increase of the air injection rate, the length of the attached cavity sheet and the size of the shedding cavity cloud increase. During the attached cavity sheet breakup and being shed process, the distance between the new partial cavity sheet and the shedding cavity cloud increase. The power spectral density (PSD) of the cavity area ( $S_{cav}/S_{throat}$ ) indicates that, with the increase of the air injection rate, the cavitation cycle decreases and the spectral content attenuates, especially the low spectral between 0-20 Hz which is supposed to be induced by unsteady sheet/cloud cavitation.

## 1. Introduction

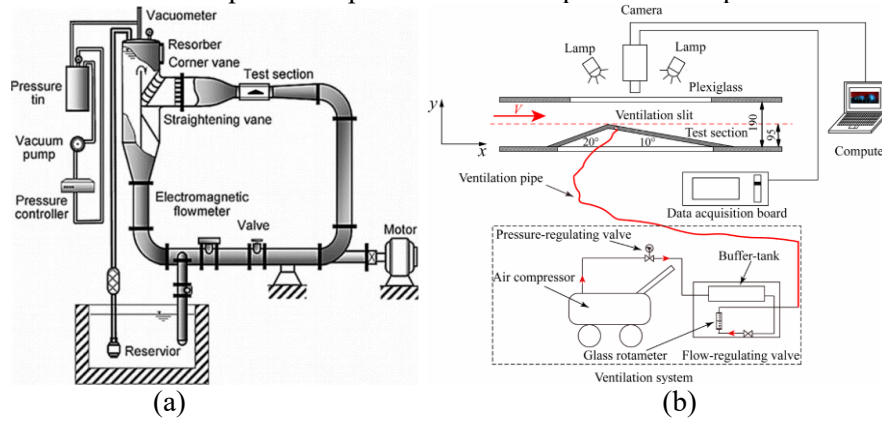
Sheet/cloud cavitation usually causes the severe oscillating phenomena known as cavitation instabilities, during which large pressure fluctuations, vibration, noise and erosion are induced [1-4]. The destructive attached cavity breakup, cavity cloud being shed and collapse process is supposed to be the main source of the cavitation damage. The control of cavitation instabilities has attracted lots of attention and the effective control technique requires deep understanding of the cavitation instabilities. Several research [5-7] has regarded the shock wave dynamics as the determinate factors of damage and noise in cavitating flows. Recently, using the x-ray densitometer technique, Ganesh et al. [8] identified the bubbly shock propagation rather than the re-entrant flow as the sheet to cloud cavitation transition mechanism in a convergent-divergent channel. Under the bubbly shock propagation induced attached cavity breakup mechanism, an obstacle placed on the wall is not efficient to prevent the sheet to cloud transition. Air injection effects in cavitation noise, vibration and erosion reduction have been investigated by several researchers [9-11]. Air injection is an effective method to change the void distribution within the cavity and thus, it will affect the bubbly shock formation and propagation characteristics associated with the bubbly shock wave propagation mechanism [12]. It is necessary to investigate the air injection effect on the unsteady sheet/cloud cavity behaviors under the bubbly shock propagation mechanism induced attached cavity breakup, cavity cloud being shed and collapse.



In the present study, a convergent-divergent nozzle is used to study unsteady sheet/cloud cavitation mechanism. The objective of this paper is to investigate the effect of air injection on unsteady sheet/cloud cavity behaviors in the bubbly shock propagation induced attached cavity breakup mechanism.

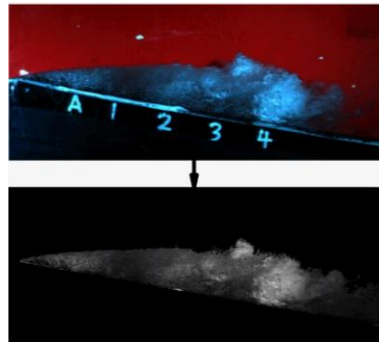
## 2. Experimental setup

Experiments are conducted in a closed-loop water tunnel in Beijing Institute of Technology, as shown in figure 1(a). The test section is a convergent-divergent channel, with a ventilation slit, linked to the ventilation system through ventilation pipe, just downstream the throat as shown in figure 1(b). We applied the high-speed camera to visualize the transient cavity behaviors. The sampling frequency of the high speed video used in the present experiment is 1500 fps and the acquisition time is 3 s.



**Figure 1.** (a) Schematic of the cavitation tunnel, (b) schematic of the measurement system.

The image processing is shown in figure 2. The rgb pictures is firstly processed to remove the background noise, leaving the cavitation region only. Then the rgb picture is transformed into gray pictures. The cavitation area  $S_{cav}$  is calculated based on the gray picture.



**Figure 2.** Schematic of the image processing.

The nondimensional air injection rate, cavitation number and Reynold number are defined as

$$C_I = C_{in} / (U_t d H), \sigma = (p_\infty - p_v) / (0.5 \rho U_t^2), Re = U_t H / \nu_l \quad (1)$$

Where  $C_{in}$  is the air injection rate,  $d$  is the throat width,  $H$  is the throat height,  $U_t$  is the throat velocity,  $\nu_l$  is the kinematic viscosity of liquid.

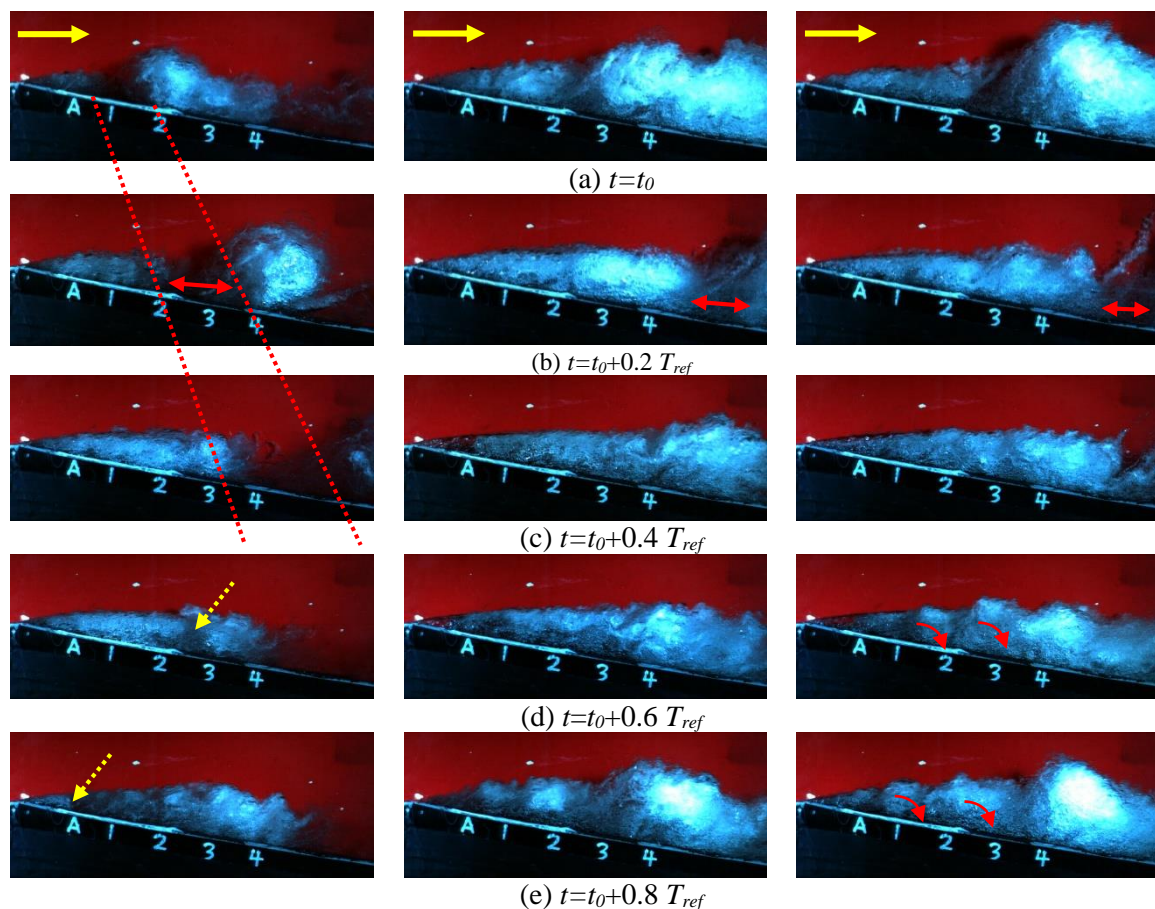
The cavitation region  $S_{cav}$  is non-dimensionalized by the throat section area ( $S_{throat} = d \cdot H$ ).

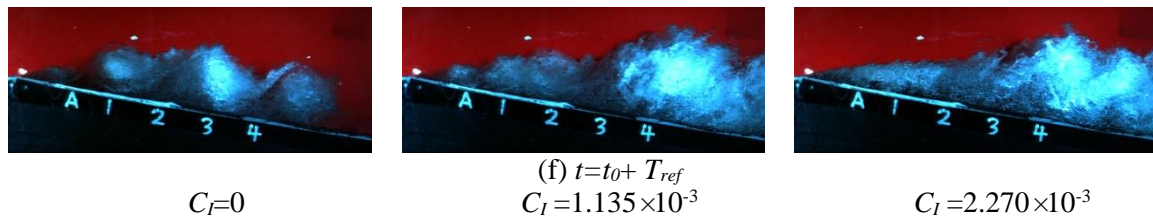
$$S = S_{cav} / S_{throat} \quad (2)$$

### 3. Results

Figure 3 shows the experimentally observed cavitation evolution during one cycle at three air injection rates  $C_F=0$ ,  $1.135\times 10^{-3}$  and  $2.270\times 10^{-3}$  for  $\sigma=0.8$ ,  $Re=0.97\times 10^6$ . The cavity cycle obtained by the cavitation images are 105 ms, 122 ms and 345 ms for  $C_F=0$ ,  $1.135\times 10^{-3}$  and  $2.270\times 10^{-3}$ , respectively. The label “A” is the position of air injection slit and positions labeled by the numbers #1, #2, #3 and #4 are uniformly 30 mm apart. The flow direction is from left to right as shown by the yellow arrows. The red arrows show the distance between the attached cavity sheet and the shedding cavity cloud. The unsteady cavity behaviors are characterized by the periodic attached cavity sheet breakup, being rolled into the cavity cloud and the cavity cloud being shed and collapse. In the present study, the shock wave front propagation as indicated by the dashed yellow arrows in figure 3(d) and figure 3(e) within the attached cavity sheet causes the attached cavity sheet breakup from throat.

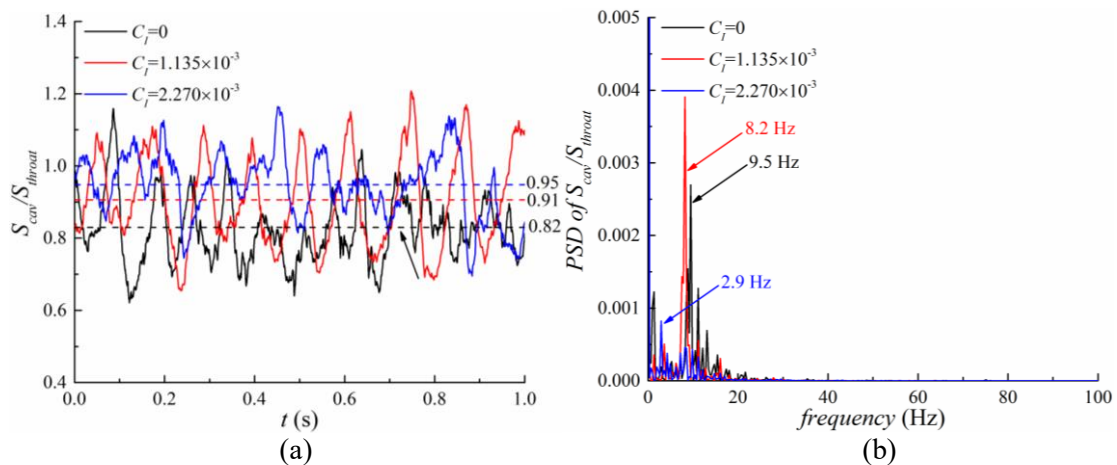
At the air injection rate  $C_F=0$ , the attached cavity sheet begins to grow near the throat at  $t=t_0$ , along with the cavity cloud downstream of it. With the cavitation development, the attached cavity sheet grow longer and the cavity cloud becomes larger in size and appears spherical in shape. As shown by the declined dashed red lines, it can be found that the shedding rate of the cavity cloud is larger than the growth rate of the attached cavity sheet. When the bubbly shock arrives at the throat, it will break up the attached cavity sheet and the next cycle begins. As the air injection rate of  $C_F=1.135\times 10^{-3}$  and  $2.270\times 10^{-3}$ , the cavitation region is evidently larger, with both the size of the attached cavity sheet and the cavity cloud larger. The distance between newly attached cavity sheet and the shedding cavity cloud decreases. The cavity interface becomes wavy. It can be found that with the air injection rate increasing, there are more small cavitation vertical structures within the attached cavity sheet. With the air injection, the bubbly shock front propagation phenomena disappears, showing the depression effect of injected air on bubbly shock mechanism.





**Figure 3.** Experimentally observed cavitation evolution at air injection rates of  $C_I=0$ ,  $1.135 \times 10^{-3}$  and  $2.270 \times 10^{-3}$  for  $\sigma=0.8$ ,  $Re=0.97 \times 10^6$ .

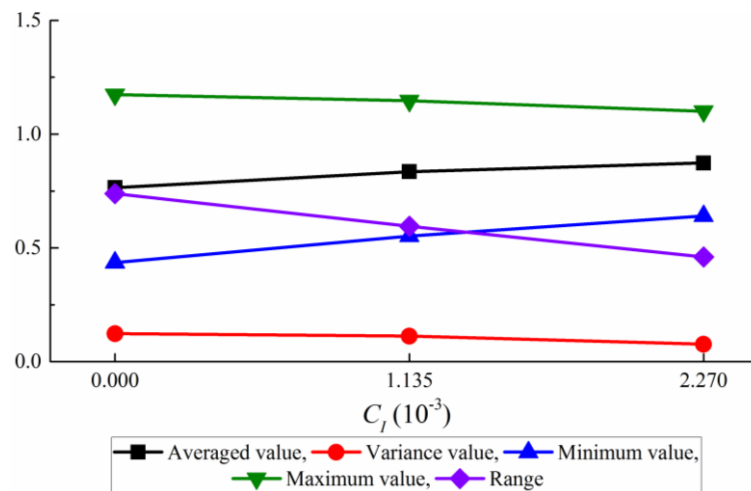
To analyze the air injection effects on the unsteady cavity behaviors quantitatively, the cavity area is calculated based on the image processing technique. Figure 4(a) gives the comparisons between the normalized cavity area evolution at air injection rate of  $C_I=0$ ,  $1.135 \times 10^{-3}$  and  $2.270 \times 10^{-3}$  and the horizontal dashed line indicated the averaged cavity area value. Figure 4(b) shows the corresponding PSD distribution at three air injection rates. It can be concluded that with the air injection rate increasing, the cavity area increases and the cavity cycle decreases. The air injected into the cavitation region makes the cavitation more stable. The spectral content attenuates with the air injection rate increases, especially in the frequency range of 0-20 Hz.



**Figure 4.** (a) Comparisons of the evolution of the normalized cavity area, (b) PSD of normalized cavity area at three air injection rate  $C_I=0$ ,  $1.135 \times 10^{-3}$  and  $2.270 \times 10^{-3}$ .

Figure 5 shows the statistics of the normalized cavity area including averaged cavity area, cavity area variance, minimum cavity area, maximum cavity area and the cavity area range. It can be found that with the air injection rate increase, the averaged cavity area and the minimum cavity area increases, while the cavity area variance, maximum cavity area and the cavity area range decrease. the decrease in cavity area variance and the cavity range shows the stability effect of injected air on the cavitation instabilities.





**Figure 5.** Statistics of normalized cavity area for averaged cavity area, cavity area variance, minimum cavity area, maximum cavity area and cavity area range.

#### 4. Discussion and conclusions

The air injection effects on unsteady sheet/cloud cavity behaviors under the cavitation condition with the bubbly shock wave propagation is experimentally investigated. Air injection will significantly depress the bubbly shock formation and propagation. With the air injection rate increase, the size of the attached cavity sheet and the shedding cavity cloud becomes larger. The distances between the attached cavity sheet and the shedding cavity cloud decreases, resulting in the cavity interface misty. The cavity evolution tends to be stable and cavitation cycle decreases.

#### Acknowledgements

The work was supported by the National Science Foundation of China (NSFC, Grant Nos: 51239005 and 51679005), National Natural Science Foundation of Beijing (Grant No: 3172029), and the Open Foundation of State Key Laboratory of Ocean Engineering (Shanghai Jiao Tong University, China).

#### References

- [1] Chen G., Wang G., Hu C., Huang B., Gao Y., Zhang M. 2015 Combined experimental and computational investigation of cavitation evolution and excited pressure fluctuation in a convergent-divergent channel *International Journal of Multiphase Flow* volume72 pp133-140.
- [2] Joseph D.D. 1995 Cavitation in a flowing liquid *Physical Review E Statistical Physics Plasmas Fluids & Related Interdisciplinary Topics* volume51 pp1649-1650.
- [3] Wu Q., Huang B., Wang G. and Gao Y. 2015 Experimental and numerical investigation of hydroelastic response of a flexible hydrofoil in cavitating flow *International Journal of Multiphase Flow* volume74 pp19-33.
- [4] Paik B.G., Kim K.S., Kim K.Y., Ahn J.W., Kim T.G., et al. 2011 Test method of cavitation erosion for marine coating with low hardness *Ocean Engineering* volume38 pp1495-1502.
- [5] Arndt R.E.A., Song C.C.S., Kjeldsen M., Keller K. 2001 Instability of Partial Cavitation: A Numerical/Experimental Approach *Symposium on Naval Hydrodynamics* France.
- [6] Leroux J.B., Coutier-Delgosha O. and Astolfi J.A. 2005 A joint experimental and numerical study of mechanisms associated to instability of partial cavitation on two-dimensional hydrofoil *Physics of Fluids* volume17 pp052101.
- [7] Wang C., Huang B., Wang G., Zhang M. and Ding N. 2017 Unsteady pressure fluctuation characteristics in the process of backup and shedding of sheet/cloud cavitation *International Journal of Heat and Mass Transfer* volume114 pp769-785.

- [8] Ganesh H., Mäkiharju S.A. and Ceccio S.L. 2016 Bubbly shock propagation as a mechanism for sheet-to-cloud transition of partial cavities *Journal of Fluid Mechanics* volume802 pp37-78.
- [9] Wang G and Cao S. 2001 Ventilation effects on cavitation erosion around a hollow-jet valve *Journal of Hydroelectric Engineering* volume1 pp48-57.
- [10] Reisman G.E., Duttweiler M.E. and Brennen C.E. 1997 Effect of air injection on the cloud cavitation of a hydrofoil *Proceedings of the Asme of Fluid Engineering Division Summer Meeting* Canada.
- [11] Arndt R.E.A., Ellis C.R. and Paul S. 1995 Preliminary investigation of the use of air injection to migrate cavitation erosion *Journal of Fluids Engineering* volume117 pp498-504.
- [12] Mäkiharju S.A., Ganesh H. and Ceccio S.L. 2017 The dynamics of partial cavity formation shedding and influence of dissolved and injected non-dondensable gas *Journal of Fluid Mechanics* volume829 pp420-458.