MECHANISM OF CLOUD CAVITATION GENERATION ON A 2-D HYDROFOIL

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Abstract

When a sheet cavity on a hydrofoil section attains a certain size, it starts violent periodical oscillation shedding a harmful cloud cavity downstream at each oscillation cycle. This phenomenon is due to the occurrence of the re-entrant jet. In this paper, the behavior of the re-entrant jet was observed in detail using a transparent foil section model and a high-speed video camera. Time variation of pressure distribution on the foil was measured simultaneously. It was found that the re-entrant jet can start at any point in sheet cavity elongating stage. Even two re-entrant jets can appear in one cycle. When a re-entrant jet is generated upstream, the jet velocity is lower compared to the case when a re-entrant jet is generated downstream. The jet velocity is almost constant at the value determined by the location of the generation. As a result, the cavity oscillation cycle becomes constant when it is normalized by the sheet cavity surface velocity and the maximum sheet cavity length. The jet velocity is calculated from the pressure gradient at the sheet cavity T.E., using a simple theoretical model. The calculated jet velocity agrees with the measurement, showing that the jet velocity increases as its generation point shifts downstream. It is possible that pressure gradient at the sheet cavity T.E. is the driving force of re-entrant jet.

NOMENCLATURE

C	Chord length of hydrofoil	(m)	σ	cavitation number	
U_∞	Uniform flow velocity	(m/s)		$\sigma = (P_\infty - P_v)/\frac{1}{2}\rho U_\infty^2$	(-)
P_∞	Referece static pressure	(Pa)	L	Sheet cavity length	(m)
P_v	Vapor pressure of water	(Pa)	L_{max}	Maximum sheet cavity length	(m)
			x	Distance from the cavity L.E.	(m)
ρ	Density of water	(kg/m^3)	V_j	Velocity of re-entrant jet	(m/s)

1 Introduction

When a sheet cavity on a body such as hydrofoils attains a certain size, it starts violent periodical oscillation shedding a harmful cloud cavity downstream at each oscillation cycle.

One of the most well-known factors of this phenomenon is re-entrant jet, which runs from downstream to upstream along the bottom of the sheet cavity, i.e. on the hydrofoil surface covered by the sheet cavity. Concerning the re-entrant jet, various researches have been made, e.g. visualization of cavity closure using dye injection (Le et al., 1993) and high-speed cinematography (De Lange et al., 1994). Kawanami et al. (1996) reported that cloud cavitation was not generated on the foil with obstacle which blocked the jet.

Recently several investigations were conducted to know the characteristics, especially velocity, of re-entrant jet. Kawanami et al. (1996) measured re-entrant jet velocity electrically and reported that it was on the same order of magnitude as the main flow velocity. Mathieu C. et al.(1998) estimated re-entrant jet velocity by visualization and pointed out that the re-entrant jet showed different behaviors depending on the thickness of the sheet cavity. Tuyêt M.P.(1998) measured the local mean velocity of the re-entrant jet using the electric probe and reported that its value increased with the distance from the L.E.

These reports are very interesting, however, information about the re-entrant jet is not enough to clarify the mechanism of cloud cavitation generation. The purposes of the present work are to understand the characteristics of the re-entrant jet more in detail and to discuss its generation mechanism. For these purposes, we carried out experiments to locate the starting point and to measure the velocity of the re-entrant jet, and finally we propose a simple theoretical model to discuss the effect of the pressure gradient as the driving force of the re-entrant jet.

2 Experimental Setup and Conditions

The experiments were carried out in the Marine Propeller Cavitation Tunnel, the University of Tokyo. The tank has a 1.0m long rectangular test section of 0.15 × 0.60 m. The profile of tested foil was NACA 0015. The model foil was 0.15m in chord length and 0.15m in span length. One hydrofoil was made of acrylic resin(Figure 1-(a)), so that one could observe the cavity and the re-entrant jet from pressure side of the hydrofoil. In order to measure the time variation of the sheet cavity length and the position of re-entrant jet, the state of cavity was filmed by a high-speed video camera with a frame rate of 9,000 frames per second (Figure 1). The other hydrofoil was made of brass(Figure 1-(b)), where six pressure pick-ups were installed on its back from 20%C to 70%C at each 10%C. Time variation of pressure distribution on the hydrofoil was measured simultaneously with the high-speed video records. The experimental conditions were determined so that re-entrant jet could be observed clearly, as follows:

angle of attack $\alpha = 8°$(fixed)

uniform flow velocity U_∞=5m/s, 8m/s

cavitation number σ=1.4, 1.6

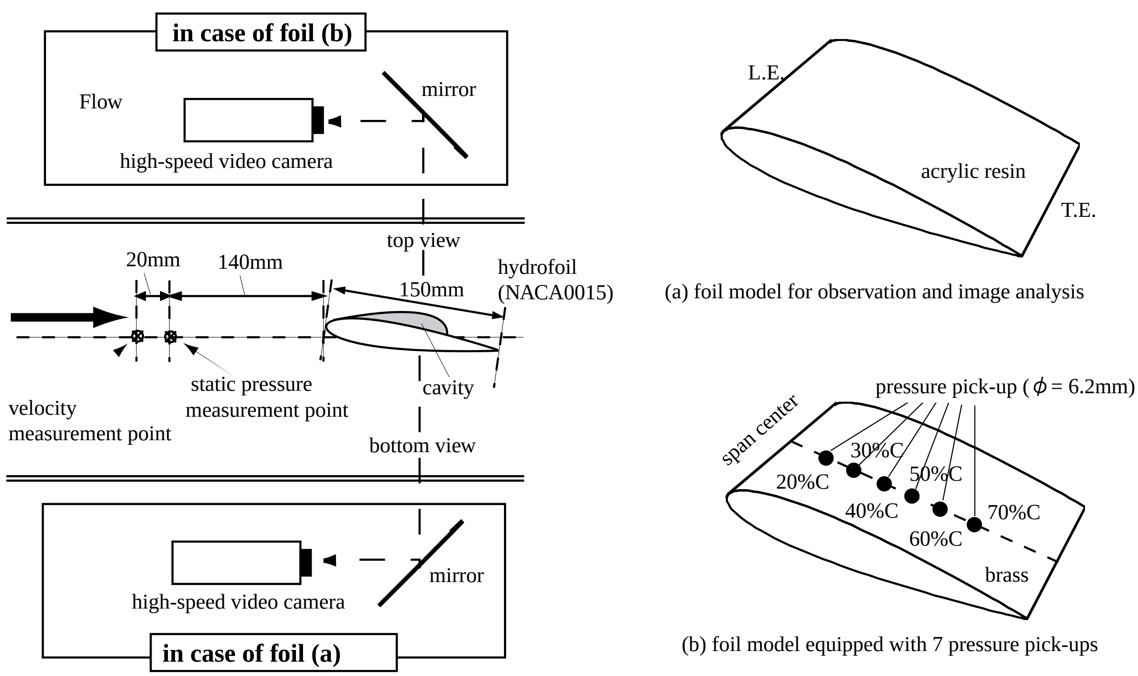

Figure 1: Experimental setup and foil models

3 Results and Discussion

3.1 High-Speed Video Observation

Figure 2 shows high-speed video images that were filmed from the pressure side of acrylic foil model. In Figure 2 white arrows represent front line of re-entrant jet.

After the separation of sheet cavity (generation of cloud cavity), a new sheet cavity appears near the foil L.E. (Figure 2-(a)), and it grows with the time(Figure 2-(b), (c)). Figure 2-(d) is a image immediately after generation of re-entrant jet. The re-entrant jet runs from downstream to upstream(Figure 2-(e)). In this case, two re-entrant jets are observed (Figure 2-(f)). The second re-entrant jet also moves from downstream to upstream, however it seems to be faster than the first one (Figure 2-(g)). The sheet cavity begins to collapse when the re-entrant jets reach the leading edge of the sheet cavity (Figure 2-(h)).

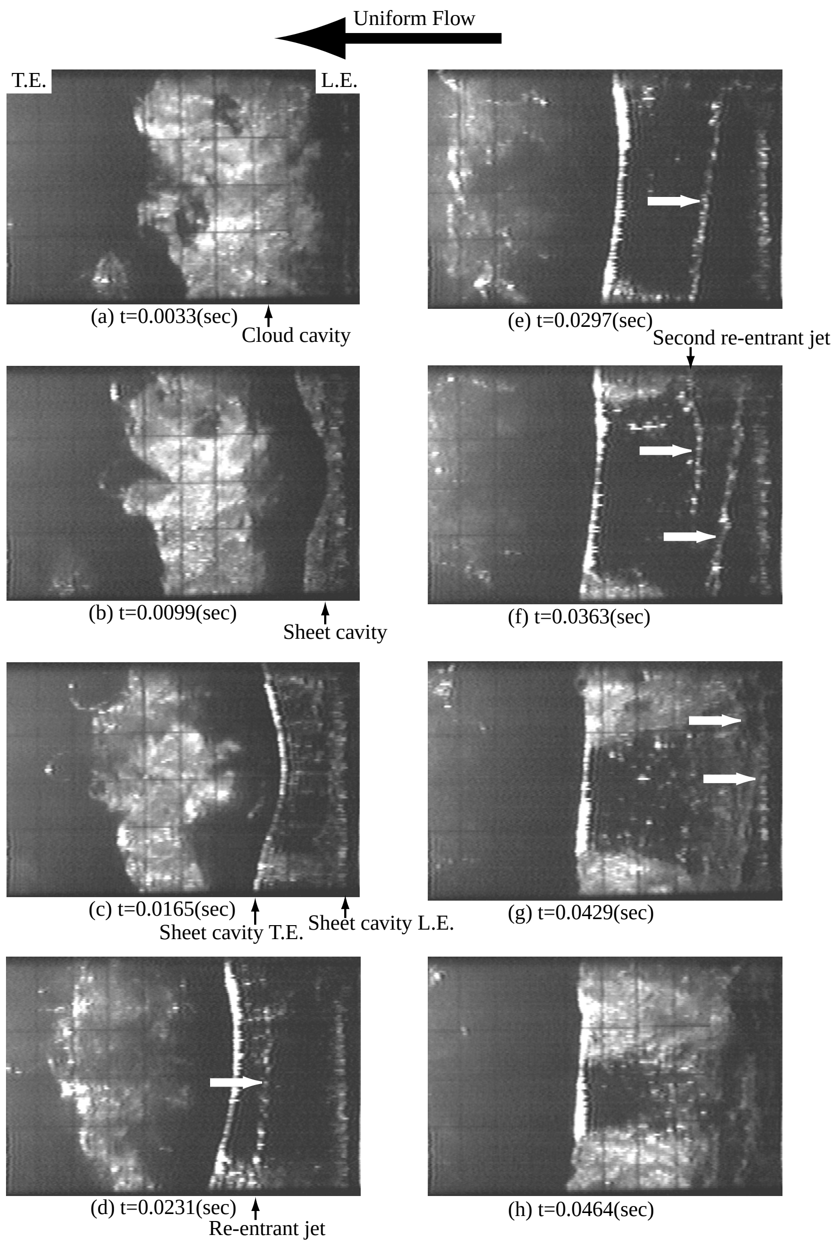

Figure 2: Typical pattern of cavity bottom view in one cycle(U_∞=5m/s, σ=1.4)

3.2 Behavior of Re-entrant Jet

In order to know the behavior of re-entrant jet in detail, we captured video images every 10 frames($\cong$ 1ms interval) and measured the length of the sheet cavity and the position of the re-entrant jet from these images. A total of 131 periods were investigated, and re-entrant jets were observed in 93 periods, which are 70.2% of the investigated periods. More than one re-entrant was sometimes observed in one oscillation cycle. A single jet was observed in 69 periods (51.9%), while two jets were observed in 24 periods (18.3%). Some examples of the time variation of the length of the sheet cavity and the position of the re-entrant jet in one cycle are shown in Figure 3. In Figure 3 the vertical axis shows a distance from the sheet cavity L.E., and the horizontal axis is the time from the release of the former cavity.

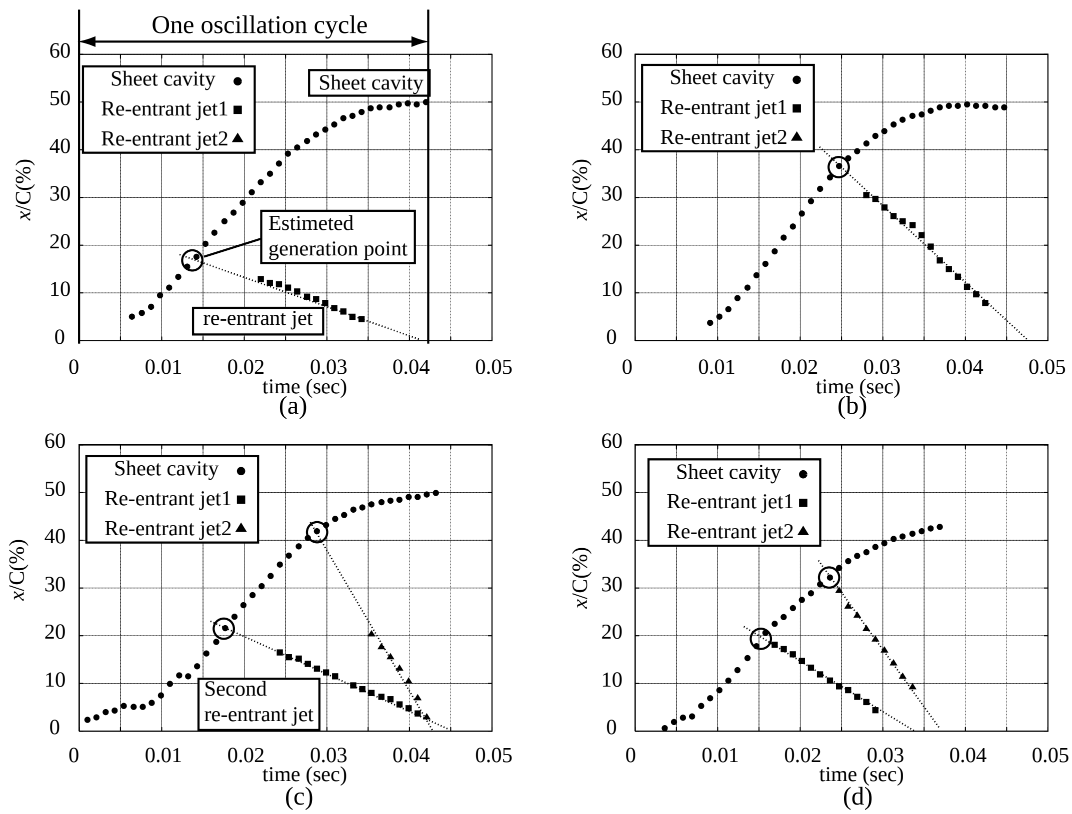

Figure 3: Examples of time variation of cavity length and re-entrant jet position in one oscillation cycle (U_∞=5m/s, σ=1.6)

Comparing Figure 3-(a) with (b), it appears that the re-entrant jet can start at any point in the sheet cavity elongating stage even under the same experimental condition. In the case of two jets (see Figure 3-(c), (d)), the second re-entrant jet is faster than the first one. It is noticed that each re-entrant jet moves almost linearly toward the upstream direction at a constant speed. This agrees with the results of Mathien C. et al. (1998).

The above results suggests that the velocity of a re-entrant jet is correlated to its starting position. We estimated the generation points of re-entrant jets by finding the cross point of the cavity end and jet trace(see Estimated generation point in Figure 3).

The measured jet velocities (V_j) are plotted against the estimated position of the generation point (x/C) in Figure 4-(a). It is noticed that re-entrant jets can appear at any point in the sheet cavity elongating stage, and that the jet speed generally increases as its generation point shifts toward the downstream direction.

Jakobsen(1964) approximated the velocity at the cavity surface by $U_\infty\sqrt{1+\sigma}$, and Kawanami(1999) showed that Strouhal number based on the cavity surface velocity, the shedding frequency of cloud cavity and the maximum sheet cavity length was almost constant. The above reports, it is assumed that velocity of

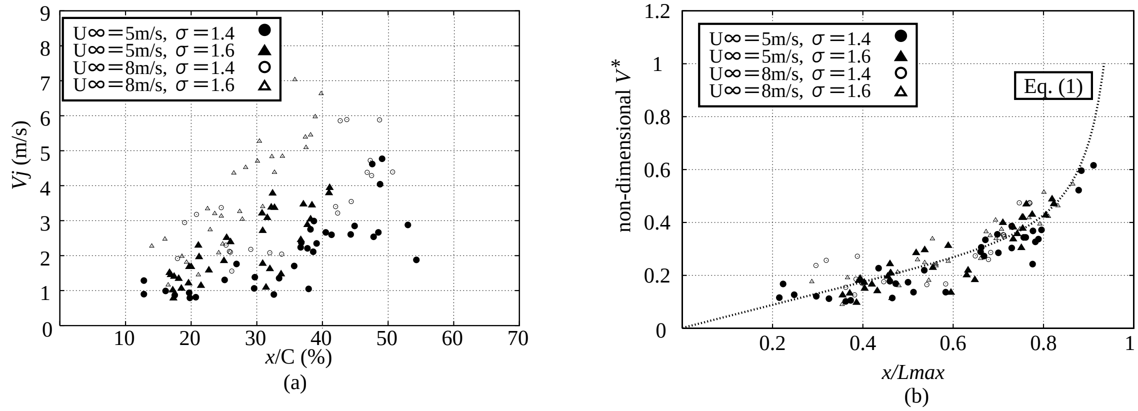

Figure 4: (a): Re-entrant jet velocity (V_j) VS. its generation point(x/C), (b): Non-dimensional velocity ($V^{*}=\frac{V_j}{U_\infty\sqrt{1+\sigma}}$) VS. non-dimensional generation point of re-entrant jet (normalized by maximum cavity length: L_{max})

the jet has a close relation to its generation position. Actually when the jet velocity normalized by the cavity surface velocity is plotted against its generation point normalized by maximum cavity length(Figure 4-(b)), all points seems to fall onto a single curve as a whole. It is satisfactory to consider that the jet velocity is almost constant at the value determined by the location of its generation, so the cavity oscillation cycle becomes constant when it is normalized as above. We propose the following empirical formula (1) for the normalized jet speed(V_j) as a function of the normalized distance(x/L_{max}) from the L.E. to the generation point of the jet.

$$\frac{V_j}{U_\infty\sqrt{1+\sigma}} = A\tan\left(\frac{\pi}{2}\frac{x}{L_{max}}\right) + B\sin\left(\frac{\pi}{2}\frac{x}{L_{max}}\right)$$
$$A = 0.0721916, B = 0.200598 \tag{1}$$

3.3 Effect of Pressure Gradient

Then, why does the jet velocity increase as its generation point shifts downstream? The measurement of the pressure distribution conducted in the present work showed that pressure gradient at the cavity T.E. became steeper as the cavity became longer. We assumed that pressure gradient at the sheet cavity T.E. was driving force of re-entrant jet.

Figure 5 shows measured pressure distribution on hydrofoil at the time sheet cavity length was 25%C, 35%C, 45%C and 55%C. A result of BEM calculation with boundary layer effect is also shown in Figure 5.

Figure 5 dipicts that C_p is almost equal to $-\sigma$ on the upstream side of the sheet cavity T.E. It indicates that the sheet cavity is filled with vapor, because C_p is defined as follows:

$$C_p = \frac{P - P_\infty}{1/2\rho U_\infty^2} \tag{2}$$

On the other hand, measured C_p at about 5%C downstream of the sheet cavity end is lower than the calculated one. This indicates the existence of a stagnant pool. Thus, the pressure gradient at the sheet cavity T.E. becomes steeper as the cavity becomes longer.

So, we calculated the jet velocity from the measured pressure gradient at cavity T.E. using a simple model. The procedure of the estimation is mentioned below. We assumed the following conditions (see Figure 6):

1. There is a stagnant pool of l in chordwise length at the sheet cavity T.E.

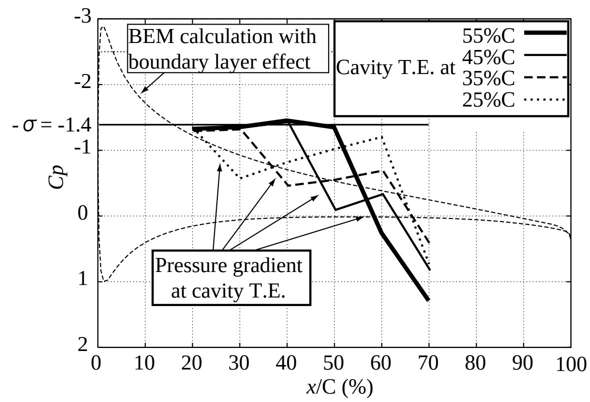

Figure 5: Measured pressure distribution on hydrofoil in various elongating stage of sheet cavity (U_∞=8m/s, σ=1.4)

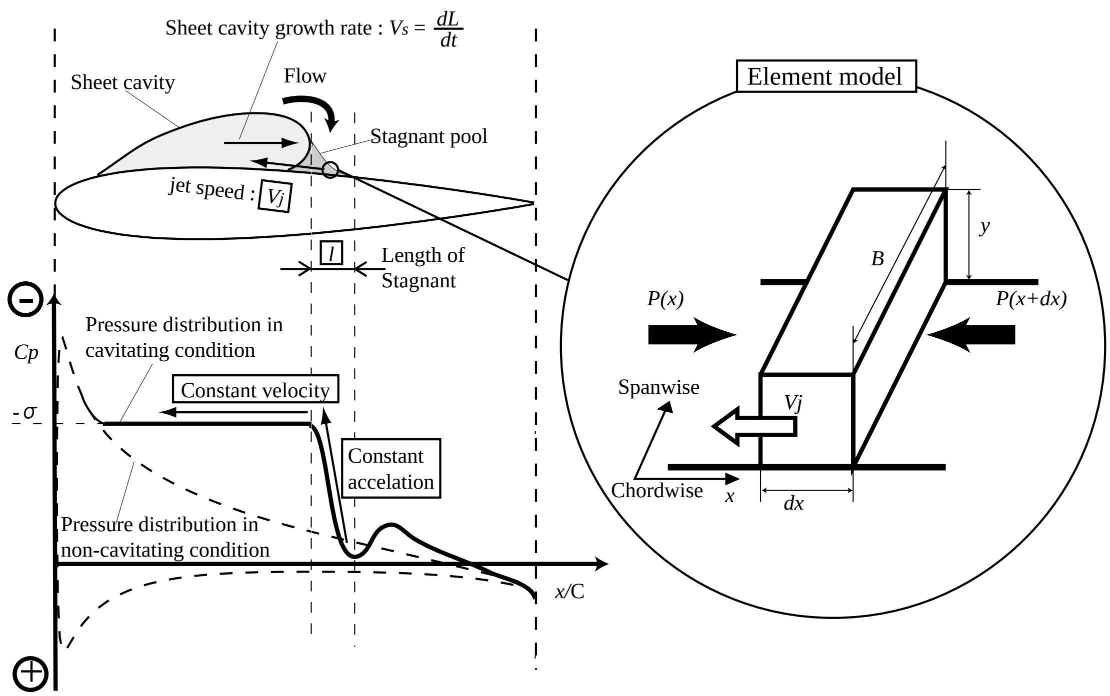

Figure 6: Calculation model

2. The pressure gradient around the sheet cavity T.E. is constant.
3. The fluid element is accelerated constantly by the pressure gradient.
4. The fluid element moves at constant velocity inside the sheet cavity.
5. There is no viscous effect.

The equation of motion of the fluid element is

$$\rho B y dx \frac{dV_j}{dt} = yB\{P(x) - P(x+dx)\} \qquad (3)$$

On the other hand, partial derivative of $C_p(x)$ with respect to x is

$$\frac{\partial C_p(x)}{\partial x} = \frac{1}{\frac{1}{2}\rho U_\infty^2}\frac{\partial P(x)}{\partial x} \tag{4}$$

By solving (3) and (4) as simultaneous equations, V_j is described as follows:

$$-\frac{dV_j}{dt} = -\frac{U_\infty^2}{2}\frac{\partial C_p(x)}{\partial x} \tag{5}$$

Using the above assumption 2, the pressure gradient at the cavity T.E. is approximated with:

$$\frac{\partial C_p(x)}{\partial x} = \frac{\sigma + C_p(x+l)}{l} \tag{6}$$

Then, (5) is rewritten as follows:

$$-\frac{dV_j}{dt} = -\frac{U_\infty^2}{2}\frac{\sigma + C_p(x+l)}{l} \tag{7}$$

The time (τ) until the fluid element reaches the cavity end is given by

$$(\int_0^\tau V_j dt) + V_s\tau = l \tag{8}$$

If (8) is solved for τ and (7) is integrated with respect to t from 0 to τ, finally Vj is described as follows:

$$V_j = -V_s + \sqrt{V_s^2 - U_\infty^2(C_p(x+l)+\sigma)} \tag{9}$$

We estimated the jet veloicity by substituting the measured values to the RHS of the Equation (9) assuming l to be 5%C. The results are shown in Figure 7.

Comparing the estimation with the experimental results, the estimated value of jet is on the same order of magnitude as the experiment results. Moreover the estimated jet velocity shows the same tendency as the experiment that the jet velocity increases with the increasing distance from the L.E. to its generation point. So, it is possible that the pressure gradient at the sheet cavity T.E. is the driving force of the re-entrant jet.

The difference between the estimation and the experiment, expect for case (b), increases as the jet generation point shifts upstream. This might be due to the hypothetic value of l, which was given as a constant value for all conditions. It is considered that the value of l requires some correction corresponding to the size of the sheet cavity. In case (b), measured C_p were rather scattered, which might be influence of the cloud cavity. So the pressure gradient at the cavity T.E. turned gentle and the estimated jet velocity became lower than those of other cases.

4 Concluding Remarks

In the present work, experiments were performed to clarify the mechanism of the generation of cloud cavitation. The main reults are summarized as follows:

- The re-entrant jet can start at any point in sheet cavity elongating stage. Even two re-entrant jets can appear in one cycle.
- When a re-entrant jet is generated upstream, the jet velocity is lower compared to the case when a re-entrant jet is generated downstream.
- The jet velocity is almost constant at the value determined by the location of its generation. As a result, the cavity oscillation cycle becomes constant when it is normalized by the sheet cavity surface velocity and the maximum sheet cavity length.
- A simple model for the jet velocity has been proposed based on the pressure gradient. The jet velocity predicted by the model agreed with the measurement, suggesting that the pressure gradient at the T.E. of the sheet cavity is the driving force of the re-entrant jet.

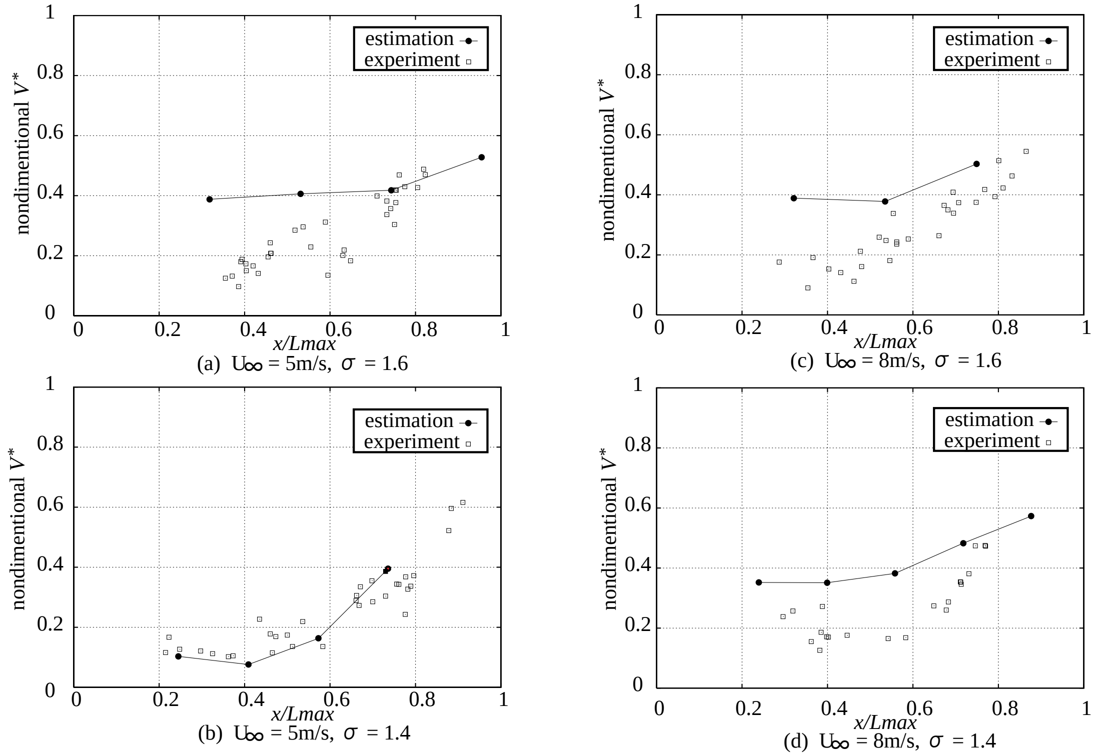

Figure 7: Comparison of re-entrant jet velocity between experiment and estimation

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