Experimental Investigation of Cavitation in an Axisymmetric Rectangular Groove*

Viet Anh TRUONG**, Jiro HIGUCHI**, Masayuki SHINTANI***
and Toshiaki IKOHAGI**

Cavitation in a 3D axisymmetric rectangular groove occurred in various types of cavitation, such as vortex cavitation, cloud cavitation, traveling cavitation and sheet cavitation. In this experimental study, some aspects of cavitating flow were clarified. Prediction and experimental calculations were also made for incipient cavitation of both the cavitating vortex ring in the groove and the sheet cavitation at the downstream of the groove. The calculations indicate that the observed cavitation is not vaporous cavitation, but gaseous cavitation. The results of this study are useful for understanding the cavitation in this type of groove structure in order to control cavitation damage.

Key Words: Cavitation, Cavitating Vortex Ring, Groove Cavitation, Inception Cavitation, Gaseous Cavitation

1. Introduction

Slots and grooves are very commonly used in gate valves and sluice and cavitation always cause trouble. Cavitating flow phenomena occurring on the slot structure have been studied as an interesting topic for many years. The first research work⁽¹⁾ of Ward on a slot with changing geometric dimensions (depth-to-width ratio $D/B=0.05$ to 3) indicated the following basic cavitation types: (I) cavitation at the downstream of the slot, (II) cavitation in a large spiral inside the slot and (III) cavitation at the center area of the slot. Ward's experiments indicated that the flow generated on the slot is not affected much by the free stream, and thus the structure of flow on the slot is not changed in cases of an incipient cavitation state as well as a noncavitating flow condition. It can be supposed that the pressure distribution on the slot is similar when using another mediums, such as air

instead of water. However, Ward's experiment did not measure and calculate pressure at the center of the slot vortex.

Holl and Billet⁽²⁾ improved the experimental study on the 2D slot model with $B/D=1$. It was confirmed again that there is not a significant influence on slot flow by free stream flow, and from the structure of the vortex flow inside the slot, the minimum pressure coefficient at the center of the vortex can be calculated by a simple integration equation. Later, Cimballa and Billet⁽¹⁾ carried out the Laser Doppler Velocimeter (LDV) experiment, which detected the velocity field on the slot and measured the minimum pressure coefficient C_{pm} inside the slot vortex by using smoke wire and a pressure probe put on the slot in a wind tunnel. Meanwhile, they also performed an experiment in a water tunnel with the same slot model at some value of air content in water. In this way, Cimballa and Billet clarified the minimum pressure coefficient C_{pm} in the slot and established the formula for predicting the incipient cavitation number σ_i of the 2D slot vortex cavitation.

In this study, the investigated problem is the cavitation phenomena for the case of a 3D slot—an axisymmetric rectangular groove (ARG) in a circular pipe. What are the changes in flow structure as well as cavitation phenomena? What is the type of cavi-

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** Institute of Fluid Science, Tohoku University, Katahira, 2-1-1 Sendai Miyagi 980-8577, Japan. E-mail: vietanh@cfs.ifs.tohoku.ac.jp, higuchij@ifs.tohoku.ac.jp, ikohagi@ifs.tohoku.ac.jp

*** Kurimoto Corp., Ltd., 8-45 Shibatani 2-chome, Suminoe-ku, Osaka 559-0021, Japan. E-mail: mshintani@kurimoto.co.jp

tion? How can the incipient cavitation be determined and predicted?

As the results of this experimental study, the outline of cavitation phenomena such as a cavitating vortex ring, attached cavitation and incipient cavitation prediction have been carried out and discussed with the goal of further understanding of cavitating flow and cavitation control in ARG structures.

Nomenclature

- B, D : width and depth of the groove [m]
 C_{pmin} : minimum pressure coefficient
 $C_{pwallmin}$: referenced minimum wall static pressure coefficient
 C_{p0} : pressure coefficient at vortex center
 C_{pE} : pressure coefficient at groove downstream edge
 K, K_s : experimental air content effect coefficient
 L_s, L_{smax} : sheet cavity length and maximum sheet cavity length [m]
 L, X : wall length [m]
 R : radius of pipe [m]
 Re : Reynolds number for main flow, $Re = U_\infty D / \nu$
 Re_B : Reynolds number for the shear flow driving vortex ring, $Re_B = U_f B / \nu$
 p_∞, U_∞ : pressure and velocity at reference point [Pa], [m/s]
 U_f : friction velocity [m/s]
 V : gas content by volume at atmosphere, $V = \frac{V_{gasdiffusion}}{V_{groove}}$
 V_θ : tangential velocity [m/s]
 V_c : tangential velocity at core radius [m/s]
 Γ_c : circulation of vortex at the core radius [m²/s]
 k, k_g, k_{gs} : gas diffusion coefficients
 k_d, k_{ds} : coefficient of reducing pressure
 p_0 : pressure at the center of vortex [Pa]
 p_E : pressure at groove downstream edge [Pa]
 p_{wmin} : referenced minimum wall pressure [Pa]
 p_{atm} : referenced atmospheric pressure, $p_{atm} = 10^5$ [Pa]
 $r_{1B} = r_1/B, r_{2B} = r_2/B$: dimensionless radius of vortex at the bottom and the top of vortex ring;
 r_1 : radius of vortex at the bottom of vortex ring [m]
 r_2 : radius of vortex at the top of vortex ring [m]
 r_D : dimensionless boundary radius of CVR, $r_D = r_{ring}/(B+R)$ where r_{ring} is boundary radius of CVR
 r_w : radius from the vortex center to the referenced minimum static pressure point on the groove wall [m]
 r_c : vortex core radius [m]

$\Delta r_{1B}, \Delta r_{2B}, \Delta r_D$: dimensionless radial fluctuation of r_{1B}, r_{2B} and r_D respectively

- α : saturated air content of experiment water [ppm]
 α_s : saturated air content of fresh water [ppm]
 α_v, α_{sh} : local saturated air content at vortex cavitation and sheet inception [ppm]
 α_l : local saturated air content [ppm]
 β : Henry constant
 ρ : density of water [kg/m³]
 σ_i : incipient cavitation number
 σ_{iv}, σ_{is} : incipient vortex cavitation number and incipient sheet cavitation number
 $\Delta\sigma$: reduction of sigma in sheet cavitation flow, $\Delta\sigma = \sigma_{is} - \sigma > 0$

2. Experimental Facilities and Procedures

The experimental system is an open-type water tunnel is shown in Fig. 1. The saturated air content of water is $\alpha/\alpha_s = 1.1$ and the water temperature is at $25^\circ \pm 1^\circ\text{C}$. The free stream velocity U_∞ is measured by an upstream calibrated nozzle and controlled in the range from 3 to 21 m/s by a downstream discharge valve and bypass valve. The test section is made of transparent acrylic resin for observing the flow aspects. The dimensions of the slot are $B = 30$ mm, the pipe diameter is $D_p = 50$ mm, $B/D = 1$. Figure 2

Fig. 1 Open-type water tunnel system

Fig. 2 Visualization measurement system

shows the experimental visualization system for studying the flow inside the groove by using a high-speed digital video camera (DVC). The gas volume of the cavitating vortex ring (CVR) is measured by a volumetric cylinder connected to the tap at the top of the groove after fast closing discharge valve. The flow visualization experiment records the motion of air bubbles ventilated from 5 mm upstream (Tap 1) in a non-cavitating flow at the top section of the groove. The size of bubbles is less than 1 mm so the fluid motion can be simulated by the motion of these small bubbles. Since the surface of the groove is curved, the recorded position of each bubble has to be corrected from the observed particle image. The vortex flow characteristics inside the groove are clarified by the particle tracking analysis of the ventilated small bubbles. For measuring the wall static pressure distribution on the ARG, 1-mm diameter taps are arranged along the wall from upstream to downstream and connected to a manometer system.

3. Results and Discussion

3.1 Cavitation phenomena

In Fig. 3, the development of cavitation on the groove occurs in the order of these four stages: (1) vortex cavitation with bubble cavitation at the groove center area; (2) CVR in a large spiral flow of bubbles and cloud cavitation; (3) traveling cavitation bubbles from inside of the CVR down to the groove downstream; (4) sheet cavitation occurring at the downstream groove edge. First, under the strobe light, the incipient cavitation is in the state of the initial, visible, rapid growth of very small bubbles at the center area on the ARG. As the liquid pressure continues to decrease, these separated bubbles pulsate and collapse to form a bigger size and then format the ring of cavitating bubbles which are oscillating at the groove center location (Fig. 3(a)). This cavitation state further develops to form the large spiral cavitating vortex ring which occupies the space inside the groove (Fig. 3(b)). The development is strong at $Re = 3.5 \times 10^5 - 5 \times 10^5$ and comes down slowly at a bigger Reynolds number when the size of the CVR reaches the boundary wall. In the large spiral cavitating flow, the collapsing and breaking of bubbles in the cavitating vortex core induces the bulk of the micro bubbles, namely cloud cavitation that is observed at the surface of the CVR. When the vortex cavitation develops at a vortex radius which is about $r_{2B} = 0.4$, cavitating bubbles from the cavitating vortex area reach the location of the main stream in the pipe and they flow together with the main flow forward to the downstream. This is called traveling cavitation. In Fig. 3(c), which shows the most development of vortex

Fig. 3 Appearance of cavitation in visualization experiment (High-speed video camera photos)

cavitation, the CVR becomes super vortex cavitation; meanwhile, sheet cavitation occurs and is fitted at the downstream area from the back edge of the groove.

Figure 4 shows the shape of the CVR is unaxisymmetric and unstable in character. The unaxisymmetric shape of the observed vortex ring can be explained by the main effect of the gravity force into the bubbles. In the noncavitating flow condition, it can be assumed that the pressure and velocity field are

(a) Cavitating vortex ring dimensionless r_{1B} , r_{2B} and r_D

(b) The fluctuation of the unstable CVR Δr_{1B} , Δr_{2B} and Δr_D

Fig. 4 The development in geometric of the unstable cavitating vortex ring

axisymmetric. But, in the cavitating flow condition, the appearance of the gas phase causes an inhomogeneous density on the volume flow of the fluid. Due to the gravity effect, depending on the size, bubbles move up to the top of the groove. That is why the dimensions of the ring decreases from the top to the bottom and r_{2B} is bigger than r_{1B} . The development in the shape of the CVR is shown by the trends of r_{1B} , r_{2B} and r_D in Fig. 4(a). The pulsation and collapse of the bubbles also induce the unstable shape of the CVR. To estimate the unstable character, the maximum fluctuated radii, Δr_{1B} , Δr_{2B} , Δr_D are detected as shown in Fig. 4(b). The peak of the fluctuation is at about $Re=4.5 \times 10^5$, when the size of the vortex ring is going to reach the wall surface.

To modify the development of the CVR, the volume of gas in the CVR was also measured. Figure 5 shows that the development of the vortex ring is related to the volume of gas contained in it. The curve of the diffused gas volume has the same trend as the development of CVR size shown in Fig. 4(a). This is clear evidence for clarifying the nature of cavitation in the CVR, namely, gaseous cavitation. The CVR size and volume are limited by a rigid wall, so that the volume of gas diffusion in the CVR seems

Fig. 5 The mass of gas diffused in cavitating vortex ring (measured in atmospheres)

Fig. 6 Unstable fluctuation of a cavity length in sheet cavitation (interval time $t=0.2$ ms, $Re=8.0 \times 10^5$, $\sigma=0.28$)

to have a critical value $V_{max} \approx 13\%$ in comparison to the groove volume.

In Fig. 6, an unstable sheet appears due to the attached cavities in the most developed groove cavitation. In this mechanism, there are shedding cavities that break off from the end of the sheet cavities and collapse in the downstream flow. The maximum length of sheet cavity L_{smax} is increasing when the cavitation number σ is decreasing as shown in Fig. 7 (a). The cavity length L_s at the state of the detected incipient sheet cavitation is assumed to be zero. Additionally, the length of the sheet cavity should be affected by the model dimensions. So it is more reasonable to introduce a relationship between the dimensionless cavity length L_s/B and the reduction of

(a) Development of sheet cavity length

(b) Dependence of maximum cavity length $L_{\max}$ on the reduction of σ as compared to σ_{is}

Fig. 7 Length of sheet cavities

σ , as compared to the corresponding incipient sheet cavitation number σ_{is} . The curve is shown in Fig. 7 (b). The fitting function is expressed as follows:

$$L_{smax}/B = 3.71 \times (\Delta\sigma)^2 \quad (1)$$

Note that $\Delta\sigma = \sigma_{is} - \sigma > 0$.

3.2 Static pressure distribution

The static pressure distribution in the groove wall is measured by the manometer at the tap positions. Figure 8(a) shows the result of the measurement for noncavitating and cavitating flow conditions. The wall static pressure in the groove is driven by a vortex ring so that it has a typical fluctuating curve, with the pressure at the center of a wall side smaller than at the corners. It is similar to the case of the 2D slot⁽⁶⁾. In Fig. 8(b), the minimum wall static pressure $P_{wallmin}$ is at center position of the upstream groove wall side ($L/R=0.6$) on the groove section and the minimum wall static pressure coefficient $C_{pwallmin}$ can be determined as a power function of Re_B :

$$-C_{pwallmin} = m(Re_B)^n \quad (2)$$

(m, n —constants)

(a) Groove wall static pressure distribution

(b) Referenced minimum wall static pressure coefficient (positioned at $L/R=0.6$) at incipient vortex cavitation state

Fig. 8 Wall static pressure distribution

In the estimation by the fitting function as shown in Fig. 8(b), the values of constants m and n were determined as $m=3.036 \times 10^4$ and $n=-1.38$.

At the downstream part from $L/R \geq 3.6$, the flow is expected to separate at the sharp back edge and reattach on the pipe wall, making a negative gradient pressure zone in between, as indicated by the results of the experimental measurement. The pressure distribution and the visualization in non-cavitating and cavitating flow suggest the type of flow passing the groove is somewhat like that in Fig. 9. The streamline model corresponds to the visualization experiment, as the smallest pressure areas are at the center of vortex core and at the back edge of the groove, where the initial vortex and sheet cavitation occurred respectively.

This result also suggests that, if the vortex structure can be estimated, the pressure at the vortex core can be calculated from the groove wall pressure. The pressure at the back edge can be simply calculated from the data at nearby positions, with consideration of the gradient of the wall pressure.

3.3 Vortex flow

The instantaneous ventilated bubble velocity

Fig. 9 Diagram of the typical flow passes over the groove

Fig. 10 Velocity vectors of small bubble motions at $Re = 4 \times 10^5$

vectors are calculated by measuring bubble displacements in the time interval $\Delta t = 0.9$ ms. The velocity vector plot is shown in Fig. 10. The vortex center is always positioned at about the groove center area ($b/B \approx 0.53$, $d/D \approx 0.57$). The characteristics of the vortex flow inside the groove are shown in Fig. 11. It can be assumed that the vortex ring is generated as a string of a Rankine vortex. The velocity field is determined by:

$$\left. \begin{aligned} r < r_c: \quad V_\theta &= V_c \frac{r}{r_c} = \frac{\Gamma_c r}{2\pi r_c^2} \\ r > r_c: \quad V_\theta &= V_c \frac{r_c}{r} = \frac{\Gamma_c}{2\pi r} \end{aligned} \right\} \quad (3)$$

The pressure gradient perpendicular to the vortex

(a) Tangential velocity V_θ (b) Circulation Γ

Fig. 11 Particle tracking analysis results

plane is the equation:

$$\frac{\partial p}{\partial r} = \rho V_\theta^2 / r \quad (4)$$

where the vortex core circulation is:

$$\Gamma_c = 2\pi r_c V_c \quad (5)$$

Under the vortex flow condition, the minimum pressure is at the vortex center. Therefore, the incipient vortex cavitation is observed first at the vortex core. The generation of the vortex ring on the groove depends more on the shear flow at the open mouth of the pipe than on the main flow of the pipe. Then, the Reynolds number Re_B based on the skin friction velocity U_f of the circular pipe is employed:

$$Re_B = U_f B / \nu \quad (6)$$

The relationships of circulation Γ_c and core velocity V_c with Re_B are shown in Fig. 12. The fitted functions are below:

$$\Gamma_c / \nu = a Re_B^b \quad (7)$$

$$V_c = c U_f \quad (8)$$

Where, the constants a , b and c were determined, such

(a) Relationship between tangential velocity V_c at the core radii and Reynolds number Re_B

(b) Relationship between circulation at the core radii Γ_c and Reynolds number Re_B

Fig. 12 Vortex core characteristics

as: $a=0.0072$, $b=1.79$ and $c=6.15$.

3.4 Incipient cavitation prediction

The referenced pressure and free stream velocity are measured at the far upstream point for calculating the cavitation number σ_i :

$$\sigma_i = \frac{p_\infty - p_v}{\frac{1}{2} \rho U_\infty^2} \quad (9)$$

If the cavitation is a pure vaporous cavitation, the incipient cavitation state will occur at $\sigma_i = -C_{pmin}^{(7)}$. With the occurrence of gaseous diffusion, the static equilibrium equation for bubbles of the gas-vapor mixture^{(3),(7)} is:

$$p_v + p_g = p_l + \frac{2S}{r_b} \quad (10)$$

In the detected incipient vortex cavitation condition, the size of the bubbles is bigger than 0.2 mm, so the term of the surface tensile S in Eq. (10) can be omitted. Then, the incipient vortex cavitation number σ_{iv} in Eq. (9) is calculated for gaseous cavitation^{(3),(4)} as:

Fig. 13 Experimental measurement prediction for incipient vortex cavitation

$$\sigma_i = -C_{pmin} + \frac{p_g}{\frac{1}{2} \rho U_\infty^2} \quad (11)$$

Where, the gas pressure p_g is calculated by Henry's law:

$$p_g = k_g \alpha_v \beta \quad (12)$$

Here, Henry's constant β depends on the water temperature, the local saturated air content α_v is calculated in ppm by moles and the gas diffusion coefficient k_g will be determined from the experiment. When the ambient pressure in the liquid is decreasing, the gas content of the diffused gas moles also changes proportionally with the local pressure at a constant temperature. Therefore, the local saturated air content coefficient α_v for the case of constant temperature is approximately determined from the saturated air content coefficient α_{sl} of water under the pressure 1 at by the equation:

$$\alpha_v = \alpha(p_0/p_{atm}) = k_d \alpha \quad (13)$$

3.4.1 Incipient vortex cavitation The result of the detection of incipient vortex cavitation is shown in Fig. 13. The incipient vortex cavitation first occurs at the center area of the vortex core, which is the lowest pressure position on the groove flow⁽⁵⁾.

In the incipient vortex cavitation condition, it can be supposed that the appearance of microbubbles do not change the pressure distribution and flow structure in the groove in comparison with the noncavitating condition. This means the minimum pressure at the vortex center is determined by integrating the gradient pressure of Eq. (4):

$$p_0 = p_{wall \min} + \frac{1}{2} \rho \left(\frac{\Gamma_c}{2\pi} \right)^2 \left(\frac{1}{r_w^2} - \frac{2}{r_c^2} \right) \quad (14)$$

From Eqs. (7), (8) and (14), k_d is inferred as a function of Re_B as below:

$$k_d = h(\log Re_B)^2 + i \log Re_B + j \quad (15)$$

Here, the values of constants h , i and j were estimated, such as $h=0.154$, $i=-0.485$ and $j=0.689$. The

minimum pressure coefficient C_{pmin} is C_{p0} at the vortex center is:

$$C_{pmin} = C_{p0} - \frac{p_0 - p_\infty}{\frac{1}{2} \rho U_\infty^2} \quad (16)$$

By Eq.(11) and (16), the predicted curve for vapor incipient cavitation can be drawn without gas diffusion effect ($k_g=0$). Comparing this to the experimental data, the difference between the values of σ_{iv} and $-C_{pmin}$ is presumably because the cavitation here is not pure vaporous cavitation but gaseous cavitation. The mass of gas diffused on the CVR also support this explanation.

Employing Eqs.(11) - (16), the incipient vortex cavitation is predicted by the following formula:

$$\sigma_i = -C_{pmin} + \frac{k_g \alpha \beta}{\frac{1}{2} \rho U_\infty^2} \quad (17)$$

Where, k_g was determined to be 0.85.

Figure 13 shows the results of the present experiment and the calculation in several value of k_g . The uniformity of the prediction curve with the experimental data proves that Eq.(17) can be used for vortex incipient cavitation calculation for the case $B/D=1$ of a 3D axisymmetric rectangular groove in a circular pipe. Compared to the 2D slot case⁽¹⁾, the trend of the curves is similar. But, in calculation form, the incipient vortex cavitation in the ARG has not been affected by fluctuating upstream pressure.

For a simpler calculation, $C_{pwallmin}$, can be replaced by C_{p0} , because the difference of pressure coefficients at the vortex center and at the minimum wall pressure position is very small in comparison with the sigma number value σ_{iv} . Employing Eqs.(2), (13) and (15), Eq.(17) is inferred as the approximate calculation below:

$$\sigma_i = -C_{pwallmin} + \frac{K \alpha \beta}{\frac{1}{2} \rho U_\infty^2} \quad (18)$$

Where, the coefficient including the effects of the pressure reducing and the gas diffusion level is defined by K which determined as following formular: $K = k_g k_d = 0.131(\log Re_B)^2 - 0.412 \log Re_B + 0.586$ and $-C_{pwallmin} = 30362 Re_B^{-1.38}$ (see Eq. 2).

3.4.2 Incipient sheet cavitation At the downstream part of the groove, there is a contraction of the flow due to the effects of separation and re-attachment, as discussed above. The minimum pressure is expected at the downstream edge by a converse pressure gradient of the convection flow in the wake. Therefore the sheet cavitation starts to occur at the downstream edge $L/R=3.6$ of the groove and lengthens in the downstream direction. The detection of sheet cavitation inception shows that the slope of the wall pressure curve remains constant, as shown in

Fig. 14 Wall static pressure distribution in downstream behind back groove edge at the incipient sheet cavitation state

Fig. 14. In consideration of the only effect of Darcy wall friction loss on the length of the wall, the pressure at the edge can be calculated by the extension from the measured data. For the pressure coefficient at $L/R=3.8$ and 4.2 , measured from taps 17 and 18 by C_{p17} and C_{p18} respectively, the wall static pressure gradient f in the vicinity of the back groove edge is:

$$f = \Delta C_p / \Delta X = (C_{p18} - C_{p17}) / [(L_{18} - L_{17}) / R] \quad (19)$$

Then, the pressure coefficient at back edge C_{pE} is:

$$C_{pE} = C_{p17} - f X_{17} \quad (20)$$

From the wall static pressure measurement, in the incipient sheet cavitation state, the pressure gradient f is a constant of about 0.035, thus:

$$C_{pE} = C_{p17} - 0.007 \quad (21)$$

And the pressure at the back edge of the groove P_E is calculated as follow:

$$P_E = (C_{p17} - 0.007) \rho U^2 / 2 + P_\infty \quad (22)$$

From the present data, the fitting function for C_{p17} can be determined as a power function of Reynolds number, such as:

$$C_{p17} = -70.6 Re^{-0.47} \quad (23)$$

Thus, the minimum pressure coefficient is performed by the function of Reynolds as below:

$$C_{pmin} = C_{pE} = C_{p17} - 0.007$$

$$C_{pE} = -0.007 - 70.6 Re^{-0.47} \quad (24)$$

From the calculated data by Eq.(22), the coefficient of reducing pressure k_{ds} is indicated as below:

$$k_{ds} = p_E / p_{atm} \quad (25)$$

The fitting function for k_{ds} is a power function of Reynolds number as the following formula:

$$k_{ds} = 0.02 (\log Re)^2 \quad (26)$$

It is similar to the calculation for incipient vortex

Fig. 15 Incipient sheet cavitation prediction

cavitation, the local air content at the back groove edge at the state of the incipient sheet cavitation is:

$$\alpha_{sh} = \alpha(p_E/p_{atm}) = k_{ds}\alpha \quad (27)$$

The cavitation number for sheet cavitation inception σ_{is} is also calculated. The prediction formula of sheet cavitation inception is indicated as the following formula:

$$\sigma_i = -C_{pmin} + \frac{k_{gs}\alpha_{sh}\beta}{\frac{1}{2}\rho U_\infty^2} \quad (28)$$

where, $k_{gs}=0.85$

A comparison of prediction formula to the experimental data is shown in Fig. 15. Since the difference between C_{pmin} and C_{p17} is not so far, for a simpler calculation, the value of σ_{is} is determined from Eqs. (23) and (28) as below:

$$\sigma_{is} = 70.6Re^{-0.47} + \frac{K_s\alpha\beta}{\frac{1}{2}\rho U_\infty^2} \quad (29)$$

Here, $K_s = k_{gs}k_{ds} = 0.017(\log Re)^2$

4. Conclusion

The results of this study have clarified some of the main problems in the case of an axisymmetric groove structure. The significant conclusions are summarized below:

(1) The experiments indicated the outline of the unstable cavitation phenomena in the 3D axisymmetric rectangular groove $B/D=1$ in a circular pipe. The cavitation appears in the order as below: *Incipient vortex cavitation* → *cavitating vortex ring* + *cloud cavitation* + *traveling cavitation* → *super vortex cavitation* + *sheet cavitation*.

(2) The shape of the unstable cavitating vortex ring (CVR) is unaxisymmetrical due to the effects of the gravity force and the wall boundary. The relative gas volume diffused in the CVR has a trend to reach the critical value in the development of the CVR ($V=$

13%). This gas volume directly affects the size of the CVR. The most unstable state of the CVR is at about $Re=4.5 \times 10^5$ where is the peak of the fluctuation.

(3) In the calculation, the structure of the vortex flow in the groove can be assumed to be like a string of a Rankine vortex.

(4) The sheet cavitation occurring at the downstream groove edge is unstable. The maximum sheet cavity length increases as the cavitating continues to develop. The cavity length can be experimentally calculated by the formula for the sheet cavitation development state:

$$L_{smax}/B = 3.71 \times (\Delta\sigma)^2$$

(5) In water with $\alpha/\alpha_s=1.1$, the cavitation in the ARG is gaseous cavitation and the inception of both vortex ring and sheet cavitation is predicted by the law:

$$\sigma_i = -C_{pmin} + \frac{k_g\alpha_i\beta}{\frac{1}{2}\rho U_\infty^2}$$

Where, $k_g=0.85$ determined by the experiment; C_{pmin} is the minimum pressure coefficient calculated at the vortex center for the case of vortex cavitation and at the back groove edge for the case of sheet cavitation.

For an approximate calculation of inception cavitation in the same quality of water, the following formulas also can be used as the semi-empirical calculation:

1. For incipient vortex cavitation of the cavitating vortex ring:

$$\sigma_{iv} = 3.036 \times 10^4 Re_B^{-1.38} + \frac{K\alpha\beta}{\frac{1}{2}\rho U_\infty^2}$$

here, $K = 0.131(\log Re_B)^2 - 0.412 \log Re_B + 0.586$

2. For incipient sheet cavitation at the back groove edge:

$$\sigma_{is} = 70.6Re^{-0.47} + \frac{K_s\alpha\beta}{\frac{1}{2}\rho U_\infty^2}$$

here, $K_s = 0.017(\log Re)^2$

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