Experimental Measurement of Vortex Cavitation around a Suction Pipe Inlet*

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Abstract Cavitation due to a suction vortex (vortex cavitation) is an important problem in some fluid machinery fields, such as fast reactors. In this study, a water experiment on vortex cavitation is carried out using a simple cylindrical vessel with a suction nozzle. In order to understand the fundamental behavior of vortex cavitation, its instantaneous occurrence behavior is grasped by visualization using high speed camera. Velocity distribution around vortex, which causes cavitation, is also quantitatively grasped by means of Particle Image Velocimetry. From visualization measurements, vortex cavitation is considered to be triggered by a wall nuclei and the cavity develops immediately toward the suction nozzle once triggering occurs on the bottom wall. In addition, distribution of pressure decrease along vortex center estimated based on Burgers model and measured velocity distribution shows monotone increase from the bottom wall toward the suction nozzle. As the results, the cavity is thought to develop toward the suction nozzle intake immediately, if some triggering of cavitation occur on the bottom wall.

Keywords: Vortex cavitation, Sodium-cooled fast reactor, Visualization on onset, PIV

1. Introduction

Cavitation, which is one of major hydraulic issues for various fluid machinery applications, is a phase change phenomena from liquid to vapor phase caused by local pressure decrease in a flow field. It is well-known that cavitation can cause noise, vibration in fluid system or/and especially erosion of material when that cavity collapses near the structural surface. Therefore, it is important to prevent the occurrence of cavitation from the point of structural integrity of fluid machinery. Also in an advanced loop-type sodium-cooled fast reactor (SFR) [1], vortex generated at the intake of outlet pipe of reactor vessel coolant can cause cavitation (See, the overview of advanced loop-type SFR and example of vortex cavitation in Fig. 1) due to pressure decrease at its center (vortex cavitation) [2]. Prevention of vortex cavitation is an important problem also in SFR from the point of structural integrity of reactor.

Fig. 1 Example of vortex cavitation at a hot leg inlet [2] and upper plenum of advanced loop-type SFR.

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In practical case, cavitation onsets are generally estimated using the cavitation factor as a non-dimensional parameter of macroscopic pressure balance. However, it is considered there is a difficulty in the evaluation of vortex cavitation onsets simply based on that kind of macroscopic parameters, since vortex cavitation is thought to be caused by quite microscopic pressure balance (local pressure decrease at vortex center). Thus, at present, mock-up experiment based evaluation is usually employed, such as the standard by American National Standard Institute [3] or Turbomachinery Society of Japan [4]. On the other hand, mock-up experiment based evaluation also has difficulties when those are adopted to different geometry from pump sumps, such as advanced loop-type SFR geometry. For instance, there are differences in flow fields and/or system pressurization (advanced loop-type SFR is under pressurization while pump sumps are generally open atmospheric system). The evaluation method of vortex cavitation, which can consider the local velocity fields and can generally be adopted to evaluate vortex cavitation, is required. Therefore, the authors have developed an evaluation method of vortex cavitation [5,6]. Related to that, there is a lack of experimental knowledge about occurrence behavior of vortex cavitation. Especially the relation between the instantaneous cavitation behavior and the local velocity fields are still unclear. Then, it is useful to conduct studies to understand fundamental behaviors of vortex cavitation in a simple geometry, including the relation between the instantaneous cavitation behavior and the local velocity fields.

In the present study, a water experiment is performed in a simple cylindrical vessel with a suction nozzle. Instantaneous occurrence behavior of vortex cavitation is observed using high speed camera. Local velocity distributions including horizontal and vertical planes around vortex cavitation are also obtained by means of Particle Image Velocimetry (PIV) [7] to understand the vortex structure which causes the cavitation. Then, the relation to occurrence behaviors of vortex cavitation is considered comparing those results.

2. Experiments

2.1 Test apparatus and experimental conditions

As mentioned in Section 1, PIV measurements are carried out in a simple cylindrical vessel with a suction pipe. Fig. 2 shows the overview of test section. The test section (left picture) is a cylindrical tank (height: 1400 mm, diameter: φ700 mm), which stands in the vertical direction. There are four side windows and one bottom window on the wall of the test section and those windows are made by transparent polycarbonate resin to visualize the inside of test section. Water flows into the test section from the upper part of the tank and flows out through a suction nozzle near the bottom. There is a flat stage of φ535 mm on the bottom of test section at the concentric position to the tank. An annular trench of 30mm depth is located between the bottom stage and side wall to dump the disturbance from the side wall. The suction nozzle, a straight pipe of 55 mm inner diameter, is inserted vertically at the center of tank. The end of suction nozzle inlet is set at 45 mm height from the bottom. Inclined blades (vane) to generate the swirling flow are also set at 690 mm above the bottom window (see, also the right side upper figure in Fig. 2). The 18 flat vanes having a certain attack angle are assembled with circumferentially equal spans to generate swirling flow. Here, the attack angle of blades from the horizontal plane is set at \( \theta_s = 18^\circ \). This swirling flow in the tank of 700 mm diameter is converged into the suction nozzle.

![Fig. 2 Overview of test section.](image-url)
The suction velocity is defined as the mean velocity at the heater and a chilling unit. The system pressure is kept constant during a measurement using an electric test loop. The water temperature can be adjusted at a constant level during a measurement using an electric test loop. Water circulates by a mechanical pump through the test loop and setting of coordinate.

**Table 1** Experimental condition in PIV measurements.

| Parameter               | Value     |
|-------------------------|-----------|
| Suction Velocity: $U$   | 5.5 m/s   |
| Water Temperature: $T$  | 20 °C     |
| Vane Angle              | 18°       |
| Height of Nozzle Intake | 45 mm     |

**Table 2** Measurement positions of PIV.

| Plane                  | $x$ | $y$ | $z$ |
|------------------------|-----|-----|-----|
| Horizontal plane (x-y) |   - | -   | 2.5 |
|                         |   - | -   | 10  |
|                         |   - | -   | 40  |
| Vertical plane (x-z)   |   - | 0   | -   |
|                         |   - | -20 | -   |

Unit (mm)

Fig. 3 shows the schematic diagram of the test loop. Water circulates by a mechanical pump through the test loop. The water temperature can be adjusted at a constant level during a measurement using an electric heater and a chilling unit. The system pressure of test loop can be controlled by pressurization of the reservoir tank. Related to the geometry, several experimental parameters are defined. Here, the suction velocity is defined as the mean velocity at the suction nozzle intake, $U$, which is monitored by an electromagnetic flow meter. The water temperature $T$ is monitored at the inlet of test section using a K-type thermocouple. **Table 1** shows experimental conditions of PIV measurements. As a typical case, $T$ is set at 20 °C and $U$ is set at 5.5 m/s respectively, where cavitation can occur under low pressurized case. The system pressure is set as the atmospheric condition during PIV measurements. Each experimental parameter is kept constant during the period of one measurement.

**2.2 Measurement condition of PIV**

The horizontal and vertical velocity distributions are obtained from PIV measurements. Fig. 4 shows the coordinate setting and the measurement area of PIV in horizontal planes. Here, the vertical direction is set as $z$ coordinate, and the horizontal two directions are also expressed by $x$ and $y$ coordinates (see, Fig. 4), where $(x, y) = (0, 0)$ is set at the center of the suction nozzle and $z = 0$ is defined at the bottom of test section. PIV measurements in the horizontal planes ($x$-$y$) around the suction nozzle are performed at three vertical positions ($z = 2.5, 10, 40$ (mm)) as shown by **Table 2** (see, Fig. 4 left also).

The typical size of measurement area is approximately 140 mm x 140 mm. Velocity vectors are calculated by the cross-correlation method with sub-pixel accuracy [8]. The typical spatial resolution of each velocity vector is 3 mm (22 x 22 pixels of reference window). The sampling interval of velocity field is 62.5 Hz. The total sampling time in one measurement is nearly 16 s (1024 times sampling at 62.5 Hz).
Fig. 5 shows the measurement area of PIV in vertical planes. Velocity distributions in the vertical planes (x-z) are grasped between the suction nozzle and the bottom of test section. The coordinates are set as same as the measurements in the horizontal planes. Two measurement positions (y = 0, -20 (mm)) of PIV are selected here as shown by table 2 (see, Fig. 5 right also). The size of measurement area is approximately, 78 mm x 78 mm. The typical spatial resolution of each velocity vector is 1.8 mm (22 x 22 pixels of reference window). The other conditions such as correlation method or sampling intervals are the same as the measurements in horizontal planes.

![Vertical position](image1)

**Fig. 5 Measurement position of PIV in vertical plane.**

![Horizontal position](image2)

3. **Experimental Results**

3.1 **Observation of instantaneous behavior of vortex cavitation occurrences**

Firstly, the behavior of vortex cavitation occurrence is discussed based on images obtained from visualization measurement. Fig. 6 shows a typical back-lighting snapshot of vortex cavitation. An upward column shaped shadow, i.e. cavity, is observed between the bottom and the suction nozzle. The position of cavity observed in this geometry is nearly along the center line of suction nozzle. Fig. 7 shows a time series of instantaneous photographs obtained by high speed camera. These photographs show the development process of vortex cavitation during 1.3 x 10^{-3} s from the onset of cavitation (T = 20 °C, U=5.0 m/s). Measurement area (nearly 20 mm squared area) is set at the vicinity of bottom wall. Sampling speed of original image is 15000 Hz. Fig. 7 (1) is the frame at t = 0 s at the time just before the cavity generation. Fig. 7 (2) at t = 6.7 x 10^{-3} s shows the first frame immediately after the generation of cavity. A small shadow of cavity is at a vicinity of bottom wall. This cavity shows monotone development upward toward suction nozzle intake through Fig. 7 (3) – Fig. 7 (8). From these result, vortex cavitation in this geometry is considered to be triggered by a nuclei on the bottom wall. In addition, it is considered that the pressure at the vortex center in the upper bulk region (between the bottom wall and the suction nozzle) already becomes under the saturated condition, i.e. meta-stable situation. Therefore, if a triggering occurs on the wall, vortex cavitation is thought to develop immediately toward the suction nozzle.

3.2 **Flow pattern between the suction nozzle and bottom of test section**

Flow pattern between the suction nozzle and the bottom of test section is discussed based on the time averaged velocity distributions obtained from PIV measurements. From the discussion about Fig. 6, cavity is observed nearly the center of suction nozzle. Therefore, PIV measurements are mainly focused on the area around center line of suction nozzle as shown in Fig. 4 and Fig. 5. Fig. 8 shows an example of time averaged velocity distribution in horizontal (x-y) planes. These three pictures show the results at z = 2.5 mm (near the bottom), z = 10 mm (at the halfway) and z = 40 mm (near the nozzle inlet), respectively from the left side. The broken circles show eye-guides of vertically projected position of the suction nozzle edge. The swirling flow, i.e. vortex, is generated nearly concentric with the suction nozzle in each z planes. The convergence of flow from the outside area toward the vortex center is also seen in each planes. However, the degree of convergence is much larger at z = 40 mm, i.e. near the nozzle inlet.
than the other planes.

Fig. 9 shows the comparison of radial and circumferential velocity distributions among three horizontal planes shown in Fig. 8 (z = 2.5 mm, 10 mm, 40 mm). The left side graph, Fig. 9 (1) shows the comparison of normalized x-direction velocity, \(-V_r/U\), at \(y = 0\) and \(x > 0\), as radial velocity distributions in horizontal plane. Horizontal axis shows the horizontal position \(x\), and the vertical axis shows the \(-V_r/U\). In each horizontal plane (\(z = 2.5\) mm, 10 mm, 40 mm), there is a peak point or a maximal point of \(-V_r/U\). \(-V_r/U\) increases nearly linearly from the vortex center toward that peak point or maximal point. As for the magnitude, the result of \(z = 40\) mm shows the largest value of \(-V_r/U\) for the overall range of \(x\) due to the influence of suction nozzle; \(z = 40\) mm is the nearest plane to the suction nozzle intake among three planes. Within the rest two cases, \(z = 2.5\) mm shows larger \(-V_r/U\) than \(z = 10\) mm. This is considered to be due to the influence of the bottom solid boundary. The right side graph, Fig. 9 (2) shows the comparison of normalized y-direction velocity, \(V_y/U\) at \(y = 0\) and \(x > 0\) as circumferential velocity distributions around the vortex center. It is seen velocity profile like the combined vortex, i.e. the combination of inside forced vortex and outside free vortex. In the free vortex region, for instance \(x = 20\) mm (broken line in Fig. 9 (2)), \(V_y/U\) takes smaller value at \(z = 2.5\) mm than the other two cases, while \(V_y/U\) at \(z = 40\) mm and \(z = 10\) mm are nearly the same value. This tendency also is considered due to the influence of the bottom solid boundary.

Fig. 7 Instantaneous development of vortex cavitation.

Fig. 8 Time averaged horizontal velocity distribution (\(U = 5.5\) m/s, \(T = 20^\circ\)C).
Fig. 9 Comparison of time-averaged \( V_x / U \) and \( V_y / U \) among three different horizontal planes (\( z = 2.5 \text{ mm}, 10 \text{ mm}, 40 \text{ mm} \)).

Fig. 10 shows the comparison of the velocity distribution at vertical planes \( y = -20 \text{ mm} \) (in front of nozzle center) and \( y = 0 \text{ mm} \) (on nozzle center line). In Fig. 10 (1) \( (y = -20 \text{ mm}) \), the strong vertical flow is observed near the nozzle intake edge due to the suction flow. And also, relatively large horizontal flow is observed along the central line of suction nozzle. In Fig. 10 (2) \( (y = 0 \text{ mm}) \), large velocity is observed as follows: i) horizontal flow along the bottom wall, ii) vertical flow along the both side of central line of suction nozzle, and iii) vertical flow at the vicinity of the suction nozzle inlet. The first one of i) is considered to be the influence of bottom solid boundary as already mentioned also in Fig. 9. The second one of ii) is due to the radially converged flow, mainly through the bottom layer, turn its flow direction upward near the central region of vortex. The third one of iii) is simply due to the suction flow. Fig. 11 shows the distribution of \( V_z / U \) in \( z \) direction. The left side graph, Fig. 11 (1) shows the \( V_z / U \) at \( x = 0 \text{ mm}, y = -20 \text{ mm} \), i.e., circumferential velocity distribution in \( z \) direction. \( V_z / U \) increases steeply near the bottom (\( z = 0 \text{ mm} \)). Then, \( V_z / U \) reaches gradually plateau region (and approximately \( z > 10 \text{ mm} \)) toward the larger \( z \) range. This means that the circumferential flow develops (accelerates) mainly at the bottom boundary layer, Ekman layer, which is consistent to the discussion in Fig. 9 (2). The right side graph,
does not influence on the development of circumferential flow in this region. It is also estimated that the strong radial flow in this region is nearly constant in this region. Therefore, it is considered that the strong radial flow in this region does not influence on the development of circumferential flow. At the vicinity of the bottom wall (approximately z < 10 mm), \( V_z/U \) decreases according to the increase of z (see i) in Fig. 10 (2) also). This relatively large \( V_z/U \) region near the bottom wall also matches the developing region of circumferential flow (compare, the non-plateau region between Fig. 11 (1) and Fig. 11 (2)). Thus, this relatively large \( V_z/U \) (radial flow) near the bottom can be understood as the fluid motion alike Ekman spiral [9] in the bottom boundary layer.

3.3 Relation between local velocity distribution and occurrence behavior of vortex cavitation

At last, distribution of pressure decrease along vortex center is estimated based on vortex model using velocity obtained distributions. Based on Burgers model [10], pressure decrease \( \Delta P \) at vortex center is estimated using circulation at infinite distance \( \Gamma_{\infty} \) and radial velocity gradient \( \alpha \) as follows [6];

\[
\Delta P = \frac{\ln 2}{16\pi^2} \frac{\rho \alpha \Gamma_{\infty}^2}{V} \quad (1)
\]

where, \( \rho \) is the density of liquid, \( V \) is the kinematic viscosity of liquid. Therefore, \( \Delta P \) can be estimated using the velocity distributions of \( \alpha \) and \( \Gamma_{\infty} \). Here, \( \Gamma_{\infty} \) and \( \alpha \) is estimated using \( V_r \) at \( x = 0 \) mm, \( y = -20 \) mm in Fig. 11 (1) and \( V_z \) at \( x = -20 \) mm, \( y = 0 \) mm respectively in Fig. 11 (2). \( \Gamma_{\infty} \) is roughly calculated as \( \Gamma_{\infty} = 2\pi V_r \). \( \alpha \) is also estimated as \( \alpha = V_r/2x \) considering the continuity equation. At \( x = -20 \) mm, \(-V_z/U\) is approximately within the area, where \(-V_z/U\) linearly increases with the increase of radial distance.

Fig. 12 Estimated pressure decrease at vortex center in vertical direction based on Burgers model.

Fig. 11 (2) shows the \( V_z/U \) at \( x = -20 \) mm, \( y = 0 \) mm, i.e., radial velocity distribution in z direction. Except near the bottom region, \( V_z/U \) increased according to the increase of z due to the influence of suction flow toward the suction nozzle. On the other hand, the circumferential flow is nearly constant in this region as mentioned in Fig. 11 (1). Therefore, it is considered that the strong radial flow in this region does not influence on the development of circumferential flow. At the vicinity of the bottom wall (approximately z < 10 mm), \( V_z/U \) decreases according to the increase of z (see i) in Fig. 10 (2) also). This relatively large \( V_z/U \) region near the bottom wall also matches the developing region of circumferential flow (compare, the non-plateau region between Fig. 11 (1) and Fig. 11 (2)). Thus, this relatively large \( V_z/U \) (radial flow) near the bottom can be understood as the fluid motion alike Ekman spiral [9] in the bottom boundary layer.

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Fig. 12 Estimated pressure decrease at vortex center in vertical direction based on Burgers model.
from the vortex center (see, Fig. 9 (1)) as the assumption of Burgers model. Fig. 12 shows the distribution of \( \Delta P/\Delta P_{\text{max}} \) in \( z \) direction. Here, \( \Delta P_{\text{max}} \) is the maximum value of \( \Delta P \) in \( z \) direction. \( \Delta P/\Delta P_{\text{max}} \) shows nearly monotone increase in \( z \) direction. And also, the maximum value of \( \Delta P/\Delta P_{\text{max}} \) is observed near the intake of suction nozzle. Therefore, if some triggering of cavitation occur on the bottom wall, cavity is thought to develop toward the suction nozzle intake immediately. And also, this is consistent to the observation in Fig. 7, i.e. the existence of meta-stable region.

4. Conclusions

In the present study, a water experiment is performed in a simple cylindrical vessel with a suction nozzle. Instantaneous occurrence behavior of vortex cavitation is observed using high speed camera. Local velocity distributions including horizontal and vertical planes around vortex cavitation are also obtained quantitatively by means of Particle Image Velocimetry (PIV). As the result, following findings are obtained.

- Vortex cavitation is considered to be triggered by the nuclei on the bottom wall and the cavity develops immediately once triggering occurs on the bottom wall.
- The circumferential flow develops mainly at bottom boundary layer and then becomes a plateau toward suction nozzle intake.
- In addition to large radial velocity near the suction nozzle, there is relatively large radial velocity region near the bottom wall due to the fluid motion alike Ekman spiral at the bottom boundary layer.
- Distribution of pressure decrease along vortex center estimated based on Burgers model shows monotone increase from the bottom wall toward the suction nozzle. Therefore, if some triggering of cavitation occur on the bottom wall, cavity is thought to develop toward the suction nozzle intake immediately.

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