Study on Behavior of Vortex Cavitation around Suction Pipes in Sodium-Cooled Fast Reactor Geometry

Toshiki EZURE†‡, Kei ITO†, Hideki KAMIDE†, and Tomoaki KUNUGI‡

Abstract

Cavitation is a key engineering issue in various turbo-machinery applications. Also in an advanced loop-type sodium-cooled fast reactor (advanced SFR), vortex type cavitation has become an important issue to be cared from the viewpoint of the integrity of structural materials of the reactor. Therefore, a method to evaluate this type of cavitation needs to be established. In this paper, vortex cavitation behavior is studied using a 1/22-scale upper plenum water model of the advanced SFR. Vortex cavitation occurrences are quantitatively grasped through visualization measurements, including the transient behavior under various conditions of inlet velocity at the suction pipe, water temperature, and system pressure. In addition, the relationships between the local velocity around a vortex and vortex cavitation occurrences are investigated based on the results from the visualization and Particle Image Velocimetry measurements. The experimental results show the difficulty of evaluating vortex cavitation occurrences based on a macroscopic parameter, i.e. cavitation factor. In contrast, the results of vortex evaluation with local circulation give a good agreement with the vortex cavitation occurrence data. Therefore, the local circulation is considered as the most important evaluation parameter.

Key Words: Vortex cavitation, Visualization, PIV measurement, Sodium-cooled fast reactor

1 Introduction

Cavitation, which is a phase-change phenomenon caused by a local pressure decrease of fluid is a key engineering issue in turbo-machinery applications. When a strong vortex is generated in a fluid system, it can cause cavitation because of a pressure decrease at the vortex center (vortex cavitation). Once vortex cavitation occurs, it may lead to noise, vibration and/or erosion problems for structural materials as seen at pump intakes or impeller blade tips. Therefore, suppressing this phenomenon is essential in most observed situations. Also in an advanced loop-type sodium-cooled fast reactor (advanced SFR) [1], vortex cavitation at the intake mouth of the outlet pipe is a concerning problem [2]. For instance, at the intake mouth of the outlet pipe of a reactor vessel, average outlet velocity reaches approximately 9.2 m/s. The swirling flow caused by the inner structure of the vessel converges at the intake mouth and generates a strong vortex between the intake mouth and structural wall, which may cause vortex cavitation in this geometry. Therefore, the prevention of vortex cavitation is an important problem also in the advanced SFR to avoid various problems caused by cavitation [2].
Standards for scale model tests related to the evaluation of vortex cavitation have been established by the American National Standards Institute [3] and the Turbomachinery Society of Japan [4]. However, these standards are primarily focused on the methodology of mock-ups in pump sump geometry. There are many differences between the advanced SFR geometry and pump sumps, such as differences in the flow fields and system pressurization; advanced SFR is pressurized, whereas pump sumps are generally open atmospheric systems, which may influence the phenomenon. Therefore, those standards are not believed to be applicable for fast reactor geometry. Evaluation parameters of vortex cavitation occurrences and/or evaluation methods for the general situation remain unclear. Therefore, an evaluation method that is generally applicable to vortex cavitation is required.

In this study, water experiments on a 1/22-scale upper plenum model of the advanced SFR were carried out to understand the behavior of vortex cavitation and to consider the applicability of the cavitation factor, which is the parameter of macroscopic pressure balance in a fluid, to the evaluation of vortex cavitation in reactor geometry such as the advanced SFR. Vortex cavitation occurrences were quantitatively grasped through visualization measurements including transient behavior under various conditions of the inlet velocity of suction pipe, water temperature and system pressure. Then, the applicability of the cavitation factor to the evaluation of vortex cavitation in the current geometry was considered, because the cavitation factor is commonly used as the index of cavitation occurrences. In addition, velocity distributions around vortex cavitation were also quantified by means of Particle Image Velocimetry (PIV). Finally, the relationships between the local velocities around a vortex and vortex cavitation occurrences were investigated.

2 Experiment

2.1 Experimental apparatus

Water experiments were carried out using a 1/22-scale upper plenum model (1/22-scale model) of the advanced SFR. Fig. 1 shows a section view of the Reactor Vessel (R/V) of the advanced SFR. The area of concern of the present study is set in the upper plenum (the area above the core outlet), where the suction pipes descend. The advanced SFR is designed as a loop-type fast reactor with two suction pipes in the R/V for the outlet of the coolant. These pipes are inserted vertically from the top of the R/V. Therefore, the suction pipe and R/V wall are parallel to one another. The upper internal structure (UIS), which is composed of control rod guide tubes and several perforated plates with radial slits, i.e., column-type UIS, is installed in the central region of the upper plenum, as shown in Fig. 1. The sodium coolant from the core outlet goes upward through the UIS towards the two outlet pipe intakes. That coolant flow, which is inevitably non-uniform and has a swirling motion, is accelerated at the H/L intakes up to 9.2 m/s. As a result, strong vortices sometimes accompanied by cavitation can be generated at the H/L intakes. In the 1/22-scale model, the area from the core outlet to the dipped plate (D/P), which prevents surface waving, is modeled (see, the broken line in Fig. 1).

An overview of the 1/22-scale model is shown in Fig. 2 (1). Also, the horizontal layout of the inner pipes is shown in Fig. 2 (2). As mentioned above, the region between the core outlet and D/P is modeled. Subsequently, there is a solid boundary at the free surface position (no free surface in the test model). Major reactor components such as the UIS, H/L, and the other tube-shaped structures (see, Fig. 2) are modeled at the similar positions to those in the advanced SFR. The core outlet is modeled by a perforated plate with the same number of holes as the real reactor’s core outlets. In order to detect the occurrence of vortex cavitation, the area between the H/L intakes and R/V wall can be visualized through the R/V wall, which is made from transparent acrylic resin. Here, the two H/L pipes are distinguished by the circumferential angle as shown in Fig. 2 (2). The H/L at the top of Fig. 2 (2) is defined as the 0 degree side, and the other side of H/L is defined as the 180 degree side, respectively. Representative dimensions of the test model are shown in Table 1.
Table 1 Specifications of test model and test loop.

<table>
<thead>
<tr>
<th>Test model</th>
<th>Area of modeling</th>
<th>Upper plenum (between core outlet and D/P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model inner diameter</td>
<td>486 mm (inner diameter)</td>
<td></td>
</tr>
<tr>
<td>Model height</td>
<td>268 mm (bottom- D/P undersurface)</td>
<td></td>
</tr>
<tr>
<td>H/L diameter</td>
<td>57 mm (inner diameter)</td>
<td></td>
</tr>
<tr>
<td>Clearance between H/L</td>
<td>16 mm</td>
<td></td>
</tr>
<tr>
<td>wall and R/V wall</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Loop</th>
<th>Working fluid</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>15 °C – 45 °C</td>
<td></td>
</tr>
<tr>
<td>System pressure</td>
<td>&lt; 0.3 MPa</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Schematics of 1/22-scale upper plenum model.

Fig. 3 Schematic flow diagram of test loop.

Table 1 shows the specifications of the test model and test loop. The representative loop specifications are also shown in Table 1. As shown in Fig. 3, the working fluid is pressurized by a mechanical pump and circulates within the test loop. The water temperature (T) is controlled by an electric heater and a chilling unit at a constant level. The system pressure (P) is controlled by means of pressurization of the reservoir tank, where the test loop has only one free surface in the system. The flow path between the reservoir tank and main loop is also regulated by a valve to regulate the exchange of fluid between the main loop and reservoir tank.

The experiment was performed using well-purified water by a means of a filter, which can remove dusts or solid-state objects and degassed water to keep a water condition constant throughout the experiments. For this experiment, T was monitored at the inlet of test section using a K-type thermocouple. P was measured by a diaphragm typed pressure gauge at the bottom level of upper plenum. V_in was defined as the mean velocity at the H/L intakes and was measured by an electro-magnetic flow meter.

2.2 Measurement of Vortex Cavitation Occurrences

Vortex cavitation occurrences were measured by a combination of visualization and image analysis. Vortex cavitation occurrences were captured by a digital CMOS camera with 200 k pixels (500 x 450) of imaging elements. A metal halide lump was used as the light source. The imaging area was set as nearly 6 cm of square region around each H/L intake: large enough to cover the overall area of H/L intake. In total 18000 continuous frames of images were captured with a 33.3 ms sampling interval (30 Hz sampling), i.e., 10 minutes of measurement for each experimental cases. These images were binarized based on a threshold decided by the discriminant analysis method [5], and the vortex cavitation occurrences in each frame were detected quantitatively.
2.3 Velocity measurement around vortex cavitation

Velocity distributions around the vortex cavitation were measured by Particle Image Velocimetry (PIV). Fig. 4 shows the measurement positions and specifications of the present measurements. An Nd-YAG laser light sheet was inserted vertically at a position midway between the H/L pipe and R/V wall (see Fig. 4 (2)). The vertical position of the measurement area was also set around the H/L pipe, i.e. vortex cavitation occurred area. Thus, vertical velocity distributions across the vortex tubes were obtained under various experimental conditions.

The size of PIV measurement area was approximately, 85 mm (W) × 70 mm (H). Velocity vectors were obtained using a cross-correlation method (22 × 22 pixel of reference window) with sub-pixel accuracy [6]. The typical spatial resolution of each velocity vector was 1.8 mm. The sampling interval of the velocity field was set at 30 Hz. The total sampling time was nearly 30 s (900 times at 30 Hz).

Table 2 Experimental condition.

<table>
<thead>
<tr>
<th>Cases</th>
<th>T (°C)</th>
<th>ν (10⁻⁶ m²/s)</th>
<th>P (kPa)</th>
<th>P (MPa)</th>
<th>Vₘ (m/s)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>15</td>
<td>1.1</td>
<td>1.7</td>
<td>0.18</td>
<td>4.0 - 6.3</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td>4.5 - 6.5</td>
</tr>
<tr>
<td>B1</td>
<td>30</td>
<td>0.80</td>
<td>4.2</td>
<td>0.18</td>
<td>4.0 - 6.5</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td>4.0 - 6.5</td>
</tr>
<tr>
<td>C1</td>
<td>45</td>
<td>0.61</td>
<td>9.5</td>
<td>0.18</td>
<td>4.0 - 6.5</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td>4.0 - 6.5</td>
</tr>
</tbody>
</table>

* Vₘ is varied typically at 0.25 m/s intervals.

2.4 Experimental condition

Table 2 shows the experimental conditions. In order to evaluate the occurrence behavior in wide range Vₘ, P and T were set as parameters. Here, T was varied to evaluate the influence of kinematic viscosity, ν, on vortex cavitation. Experiments were then carried out under three different T conditions: T = 15 °C (Cases A), T = 30 °C (Cases B) and T = 45 °C (Cases C), where ν at 45 °C becomes nearly half with compared to that in 15 °C. The influence of P was also investigated under two conditions of P = 0.18 MPa (Cases A1), and P = 0.30 MPa (Cases A2), in absolute pressure. Vₘ was varied at several values (typically, 0.25 m/s intervals) between 4.0 m/s and 6.5 m/s under the various T and P conditions. Under these conditions, Reynolds number at the H/L intake was 10⁵ order. Therefore, experiments were performed in a well-developed flow field. The characteristic velocity U of the vortex was assumed to have a linear relationship with Vₘ. Then, the cavitation factor σ was calculated using Vₘ as follows;

\[ \sigma = \frac{P - P_v}{\frac{1}{2} \rho V_m^2} \]

where, Pᵥ is the vapor pressure, and ρ is the density of fluid. Each experimental condition was maintained at constant during the individual measurements.

3 Results and Discussions

3.1 Vortex cavitation observed in 1/22-scale model Experiment

In this paper, the experimental results are mainly focused on vortex cavitation behavior at the 180 degree side of the H/L, i.e. lower side in Fig. 2 (2). Fig. 5 shows an instantaneous snapshot of the vortex cavitation observed at the 180 degree side of the H/L intake.
picture was taken from outside the R/V at almost the anterior, i.e. 180 degree direction. The vortex cavitation is observed to stretch upward as an arc-shaped white line from a point on the R/V wall surface toward the inside of the H/L pipes. The vortex that causes the vortex cavitation is also thought to be formed around this arc-shaped white line.

Fig. 6 shows the typical time trends of vortex cavitation occurrences ($V_{in} = 6.5 \text{ m/s in Cases C1}$). Here, the horizontal axis shows the instantaneous time. The vertical axis shows only the onset of cavitation (upper line shows cavitation occurrences). Vortex cavitation occurrences show intermittent and aperiodic behavior. For instance, vortex cavitation occurred repeatedly having short successive time of cavitation around 20 s, while long successive occurrences were shown at about 60 s. Considering the intermittent behavior of vortex cavitation occurrences, yield fraction (Y.F.) was used as an index to evaluate the behavior (intensity) of vortex cavitation occurrences intensity.

Here, Y.F. was defined as follows;

$$Y.F. = \frac{N_{cavi}}{N_{all}}$$

(2)

where, $N_{cavi}$ is the number of frames in which cavitation is observed, and $N_{all}$ is obtained from the image analysis, as mentioned in section 2.2. The total frame number $N_{all} = 18000$. Therefore, Y.F. shows the occurrence rate (time-averaged) of vortex cavitation

Fig. 6 Typical time trends of vortex cavitation occurrences ($V_{in} = 6.5 \text{ m/s in Cases C1}$).

$$\sigma \text{ varies with the variation of } V_{in}$$. Three different symbols, i.e., Cases B1-1, Cases B1-2 and Cases B1-3, show three measurement times to check the repeatability of the phenomenon, while discrepancies between three symbols are small. Y.F. shows that the monotone increase with decreasing $\sigma$ in the constant temperature and pressure condition. This tendency is due simply to the increase in $\Delta P$, according to the increase of $V_{in}$.

3.2 Influence of kinematic viscosity on vortex cavitation occurrences in 1/22-scale model experiment

In order to see the influence of $\nu$, the relationships between Y.F. and $\sigma$ were compared between three different $T$ conditions for Cases A1, B1 and C1 ($P = 0.18 \text{ MPa, i.e., low pressure cases}$), as seen in Fig. 8 (1). The rising positions of Y.F., i.e. the point at which they starts to increase from zero, shifts to the right (large $\sigma$) side according to the decrease in $\nu$. In the same way, Fig. 8 (2) shows a comparison of Y.F. for Cases A2, B2
and C2 (\(P = 0.30\) MPa, high pressure cases). Nearly the same tendency is seen as in Fig. 8 (1) for the influences of \(v\), whereas Y.F.s in Fig. 8 (2) generally takes smaller values than those in Fig. 8 (1) due to the increase of \(P\). In each graph, it is observed that vortex cavitation became to occur easily under the smaller \(v\) conditions.

As a result, \(\sigma\), which considers only the macroscopic pressure balance of the fluid as shown in Eq. (1), is thought to have difficulty organizing the occurrences data of vortex cavitation at least in the present small scale model. This is perhaps due to an insufficiency in the evaluation of the pressure decrease at the local vortex. This means that the importance of the consideration of local vortex behavior when evaluating vortex cavitation occurrences.

### 3.3 Local velocity distribution and cavitation occurrences

In previous sections 3.1 and 3.2, the time-averaged and macroscopic behavior of vortex cavitation occurrences is mainly discussed. Next, the relationship between the local velocity distribution and vortex cavitation behavior including occurrences, is discussed. Figs. 9 (1) and 9 (2) show an example of a time-averaged velocity vector distribution around a vortex generated between the 180 degree side of the H/L intake and R/V wall for Cases C1 at \(V_{in} = 6.5\) m/s. The left side of Fig. 9 (1) shows distribution of velocity vectors around the H/L intake. A counterclockwise swirling flow is observed slightly to the left (270 degree side) of the H/L center. The right side graph in Fig. 9 (2) shows the vertical velocity distribution along a horizontal line through the vortex center (broken line in Fig. 9 (1)) as a circumferential velocity distribution. The vertical velocity decreases almost inversely proportionally to the increase in distance from the vortex center, at least outside the range more than ±10 mm from the vortex center. The present measurement is thought to capture at least the fluid motion in the free vortex region far from the vortex center.

Based on the velocity distribution obtained from the PIV measurements, the relationships between local velocities around the vortex and temporal vortex cavitation occurrences were investigated. Here, circulation was used as an index of local vortex strength and was calculated from the PIV results as follows [7];

\[
\Gamma = \oint_C \mathbf{u} \cdot ds
\]  

where, integral path \(C\) is set as the isoline of the second invariant of a velocity gradient tensor. \(\mathbf{u}\) is velocity vector. \(ds\) is the vector element along the isoline. In this study, \(\Gamma\) was evaluated as a value in free vortex region by expanding \(C\) radially.

Fig. 10 shows the relationship between a time variation of circulation around the vortex at \(V_{in} = 6.5\) m/s in Cases C1 and the instantaneous occurrences of vortex cavitation. Here, circulation \(\Gamma\) (solid symbols) is the circulation in the free vortex region. In the actual calculation of \(\Gamma\), the moving averaged value of instantaneous velocity distribution during 1 s is used as \(\mathbf{u}\). Vortex cavitation occurrences at instants, which are detected from instantaneous visualized PIV images, are shown as vertical lines. Vortex cavitation occurrences are observed mainly at instants around the local maximal of \(\Gamma\). In other words, the time trend of \(\Gamma\) shows that the behavior is consistent with vortex cavitation occurrences. From this result, it is clear that local vortex motion, i.e., \(\Gamma\), is a key to evaluate the behavior of vortex cavitation occurrences.

As the final step, experimental results for the occurrences data of vortex cavitation, which cannot be organized using \(\sigma\) as described in section 3.2, were considered again to show the validity of vortex evaluation using local \(\Gamma\). Here, the pressure decrease at vortex center, \(\Delta P_0\), was calculated with a vortex model, i.e., the Burgers model [8], using local \(\Gamma\) and the calculated value was employed as the evaluation parameter instead of \(\sigma\). The Burges model provides \(\Delta P_0\),
as follows [7];

\[
\Delta P_l = \frac{\ln 2}{16\pi^2} \frac{\rho \alpha f_\infty^{-2}}{v}
\]

(4)

where, \( f_\infty \) is the circulation at an infinite distance from the vortex center and is estimated by \( f \) in Eq. (3). Here, \( \alpha \) is the axial velocity gradient. \( \alpha \) is assumed to have a linear relationship with \( V_{\infty} \). Fig. 11 shows the relationship between the pressure decrease at vortex center and the Y.F. for vortex cavitation occurrences in Cases B1 and Cases C1. In the figure, \( \Delta P_l \) is represented by normalized value of \( \Delta P_l^* \) (normalized by the maximum value of \( \Delta P_l \), i.e., \( \Delta P_l \) for Cases C1 at \( V_{\infty} = 6.5 \text{ m/s} \)). Different cases (Cases B1 and Cases C1) are plotted nearly on a single line, that is, the difficulties in organizing the experimental results using \( \sigma \) are overcome (see, Fig. 8 (1)). This result supports the idea that consideration of local vortex motion, especially \( f \), is essential for evaluating vortex cavitation occurrences. It also is suggested that an evaluation method based on a vortex model which can consider parameters about local vortex motion, such as circulation, is an effective approach at least for vortex cavitation in this kind of similar geometry of a real reactor.

4 Conclusions

In this study, water experiments were carried out in a 1/22-scale upper plenum model of an advanced loop-type sodium-cooled fast reactor. Vortex cavitation occurrences were quantitatively grasped through visualization measurements, including their transient behavior under various conditions of the inlet velocity of the suction pipe, water temperature, and system pressure. Based on the experimental results, the applicability of a cavitation factor to the evaluation of vortex cavitation in the current geometry was considered. In addition, the velocity distribution around the vortex cavitation was also quantified using Particle Image Velocimetry. Finally, the relationships between local velocities around a vortex and vortex cavitation occurrences were investigated.

From the results, organizing the vortex cavitation occurrences data based on cavitation factor as a macroscopic pressure balance was considered to be difficult. On the other hand, time trend of circulation around local vortex (local \( f \)) shows a consistent behavior with intermittent vortex cavitation occurrences. Those results indicate the importance of local \( f \) on the evaluation of vortex cavitation. In fact, the experimental results on occurrences of vortex cavitation could be organized successfully by using a vortex model which evaluates the pressure decrease based on local \( f \). In other words, the difficulty observed in the vortex evaluation using the cavitation factor can be overcome by employing local \( f \). Thus, the evaluation considering the local vortex motion is an effective way for the vortex cavitation in a real reactor.

References
