MEASUREMENT OF THERMAL PARAMETER AND REYNOLDS NUMBER EFFECTS ON CAVITATION INSTABILITY ONSET IN A TURBOPUMP INDUCER

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ABSTRACT
The effects of non-dimensional thermal parameter and Reynolds number on cavitation instability onset in a turbopump inducer have been measured in water. From time-resolved casing pressure measurements, rotating cavitation and asymmetric attached cavitation have been identified. As the non-dimensional thermal parameter increases for a given Reynolds number, the onset cavitation number of rotating cavitation instability is decreased. For non-dimensional thermal parameter values below 0.105, the onset cavitation number of rotating cavitation instability is insensitive to Reynolds number. However, the onset cavitation number of rotating cavitation instability increases with the Reynolds number for non-dimensional thermal parameter values above 0.105. Flow visualization results qualitatively confirm the effects of each parameter.

INTRODUCTION
Turbopumps rotate at high speeds to reduce the size and weight of the liquid propulsion rocket engines, and this requirement unavoidably leads to cavitation. Therefore, an axial type inducer is often installed upstream of the turbopump to inhibit cavitation. However, the inducer itself can suffer from cavitation. When the inducer cavitation becomes severe, head coefficient, ψl, is decreased. Critical cavitation number (defined to be the cavitation number at which the head coefficient value decreases to 97% of the normal head coefficient value) is used to quantify the beginning of the head coefficient degradation. Inducer cavitation can also cause hydraulic instabilities- rotating cavitation, asymmetric attached cavitation, and cavitation surge [1]. Onset cavitation number is used to quantify the beginning of cavitation instability.

Cryogenic fluid or hot water has thermal effects on cavitation growth. The temperature and vapor pressure within the cavitation bubbles are decreased due to the latent heat during the vaporization process. This phenomenon is referred to as the “thermal effect”. As liquid temperature increases, the thermal effect is enhanced and cavitation growth is suppressed [2]. Bremen [2] suggested a dimensional thermal parameter, Σ (m/s3/2), from the Rayleigh-Plesset equation governing the dynamics and heat transfer of a spherical cavity bubble. Σ represents the amount of vapor pressure depression due to the thermal effect in a fluid (Eq. (1)).

\[ \Sigma = \frac{(\rho v L)^2}{\rho l C_p T_{inj} \sqrt{\alpha}} \]  

(1)

For cavitation in fluid machines, Franc et al. [3] derived a non-dimensional thermal parameter, Σ∗, by nondimensionalizing the Rayleigh-Plesset equation (Eq. (2)). For simplicity, they assumed inviscid flow.

\[ \frac{\ddot{R}}{2} + \frac{3}{2} \frac{\dot{R}}{U} + \frac{3}{2} \dot{R} + \Sigma^* \sqrt{x} \frac{d R}{d x} = -\frac{C_p + \sigma}{2} \]  

(2)

In Eq. (2), \( \Sigma^* = \sqrt{C_p U^3} \); the bubble radius (R) and the distance (x) have been non-dimensionalized by the characteristic length (C); \( C_p \) is the pressure coefficient; and \( \sigma \) is the cavitation number. In addition to the fluid properties of \( \Sigma, \Sigma^* \) incorporates the characteristic length (C) and reference velocity (U) of the pump, and represents the amount of the thermal effect considering length and velocity of fluid machines. In Eq. (1), as the temperature of the working fluid increases, the vapor density increases faster than the increase in the temperature; thus, \( \Sigma \) is increased. According to Eq. (2), \( \Sigma^* \) is increased as the liquid temperature increases or reference velocity decreases.

Ruggeri and Moore [4] measured cavitation performance for pumps and inducers in liquid hydrogen. The critical cavitation number in the pumps and inducers were decreased with increasing liquid temperature and decreasing rotational speed. Kikuta et al. [5] found that the critical cavitation number and cavitation region length were decreased as liquid nitrogen temperature increased. Torre et al. [6] found that the critical cavitation number was reduced at high water temperatures.

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Franc et al. [7, 8] measured the cavitation region length at the inducer leading edge and cavitation instabilities at various temperatures of refrigerant R-114 and water. The onset of rotating cavitation occurred at lower cavitation numbers as the R-114 temperature increased. The cavitation region length was insensitive to the rotational speed in cold water (in which the thermal effect was negligible), but the cavitation region length increased as the rotational speed increased in R-114 (in which the thermal effect existed). Finally, the shape of cavitation region on the inducer blades was insensitive to the R-114 temperature. According to Yoshida et al. [9, 10], the onset cavitation number of rotating cavitation was decreased as the temperature of liquid nitrogen increased. They also found shaft vibration and rotating cavitation amplitudes were reduced at high liquid temperatures. Cervone et al. [11] found that the intensity of cavitation surge was reduced at higher water temperatures. Jackson et al. [12] reported that rotating cavitation was completely suppressed at higher water temperatures.

To consider the thermal effect with non-dimensional parameter, several researchers have investigated the effects of $\Sigma^*$. Watanabe et al. [13, 14] independently derived the non-dimensional thermal parameter $\Sigma^*$ in their analysis of an inducer cascade. They found that the onset of cavitation instabilities was suppressed as $\Sigma^*$ increased. Kikuta et al. [15] investigated the rotational speed effects using $\Sigma^*$ in liquid nitrogen. They found that the cavitation region length and critical cavitation number were decreased as $\Sigma^*$ increased. Hot water can be used as a surrogate for cryogenic oxidizer or propellant matching up the non-dimensional thermal parameter in water with the cryogenic flow. Ehrlich and Murdock [16] derived their DB parameter, which is a reciprocal of $\Sigma^*$, and matched DB value in water with liquid oxygen condition. They found that rotating cavitation was completely suppressed as DB decreased in water. Kim and Song [17] also simulated cryogenic conditions with hot water by matching $\Sigma^*$. They reported that the rotating cavitation onset cavitation number was lowered as $\Sigma^*$ increased for $\Sigma^* < 0.54$ in water, however, the onset cavitation number of rotating cavitation was independent of $\Sigma^*$ for $\Sigma^* \geq 0.54$.

Previous researchers investigated the thermal effect by varying either the rotational speed or liquid temperature, and they did not consider viscous effects. However, when either the liquid temperature or rotational speed is changed, not only $\Sigma^*$ but also the Reynolds number ($Re = 2\rho air \Omega^2 \ell / \mu_1$) is simultaneously changed. Yet, the individual effects of $\Sigma^*$ and Re on the cavitation instability onset have not been examined. Therefore, the research objective of this study is to measure and understand the individual effects of $\Sigma^*$ and Re on the onset of cavitation instability in a turbopump inducer.

**Non-dimensional parameters in cavitating inducer**

To identify non-dimensional parameters governing cavitation growth in an inducer, the Rayleigh-Plesset equation for bubble dynamics is presented in Eq. (3) [18].

\[
\frac{d^2R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 + \Sigma \frac{dR}{dt} \sqrt{I} + \frac{4\mu L dR}{\rho L} \frac{2S}{R} \left( \frac{\rho_{in}}{\rho_{out}} \right)^{\gamma k} = \frac{p(t)}{\rho L}
\]

Following Franc et al. [5], time is normalized by $x/U$ where $x$ is the distance along the streamline followed by the bubble; $U$ is the inducer blade tip rotational speed; and the inducer radius is the characteristic length $C$. Surface tension ($S$) and non-condensable gas effects ($p_{in}$) are negligible after the initial stage of bubble formation [19]. The resulting non-dimensional Rayleigh-Plesset equation is then:

\[
\frac{d^2\tilde{R}}{d\xi^2} + \frac{3}{2} \left( \frac{d\tilde{R}}{d\xi} \right)^2 + \left( \Sigma^* \sqrt{\xi} + \frac{4}{Re R} \right) \frac{d\tilde{R}}{d\xi} = -\frac{cp+\sigma}{2}
\]

Increasing liquid temperature increases both $\Sigma^*$ and Re. Increasing inducer blade tip velocity increases Re but decreases $\Sigma^*$.

**Experimental Apparatus and Procedure**

Figure 1 shows a schematic of the turbopump inducer water test facility at Seoul National University [17]. The test facility has been designed to measure cavitating and non-cavitating inducer/pump performance over a wide range of operating conditions. The closed loop test facility includes a water tank, test section, flow straightener, control valve, and booster pump. A vacuum pump and compressed air supply pipe are connected to the 0.9 m$^3$ water bank to control pressure. To adjust the water temperature, a 20-kW electrical heater has been employed in the water tank. The filtered water from the tank is circulated in the direction shown in Fig. 1. Downstream of the collector, a flow straightener is located upstream of the flow meter for accurate flow rate measurement, and the

![Figure 1. SNU turbopump inducer experimental facility.](image-url)
control valve sets the flow rate. Farther downstream, the booster pump maintains a constant flow rate under cavitating conditions. Elastic couplings have been installed at the exit of the water tank and collector for alignment and vibration control. Rotating parts are composed of the test inducer, shaft, and motor. A 60-kW motor drives the inducer at rotational speeds of up to 10,000 rpm. The rotational speed of the motor is controlled to within ±1 rpm by a variable frequency drive.

Figure 2 shows the test section instrumentation locations [17]. Eight and four static pressure taps at x/D = -1.0 (P1) and 0.75 D (P2) are used to measure the inducer static head coefficient and cavitation number. Eight unsteady pressure transducers with an accuracy of 0.1 % of the full scale value (350 kPa) and 400 kHz frequency response have been installed at x/D = -0.25 to detect cavitation instabilities. Unsteady pressure signals have been sampled at 50 kHz for 1 second. Water temperature has been measured in the bulk flow and maintained constant within ±0.1 K during the test.

The mean flow rate has been measured downstream of the flow straightener using an electro-magnetic flow meter with an accuracy of 0.25 % of the full scale value (20 kg/s). The uncertainties of the head coefficient (\(\psi\)), flow coefficient (\(\phi\)) and cavitation number (\(\sigma\)) with a 95 % confidence interval are ±0.00398, ±0.000422, and ±0.000759, respectively. All of the data presented in the paper have been acquired at the design flow rate condition.

The test inducer (Fig. 3) has been designed by the Korea Aerospace Research Institute (KARI), and specifications of the inducer are summarized in Table 1. The inducer has a high solidity and moderate blade tip angle at the inlet [20].

Table 1. Design characteristics of the test inducer.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (D)</td>
<td>0.094 m</td>
</tr>
<tr>
<td>Design flow coefficient ((\phi_d))</td>
<td>0.096</td>
</tr>
<tr>
<td>Blade number</td>
<td>3</td>
</tr>
<tr>
<td>Solidity at tip</td>
<td>2.7</td>
</tr>
<tr>
<td>Blade tip angle</td>
<td>Inlet ((\beta_{1bt})) 9.6 deg</td>
</tr>
<tr>
<td></td>
<td>Outlet ((\beta_{2bt})) 15.0 deg</td>
</tr>
<tr>
<td>Non-dimensional tip clearance (c/D)</td>
<td>0.0106</td>
</tr>
</tbody>
</table>

**Experimental Results and Discussions**

**Critical Cavitation Number and Cavitation Instabilities**

Figure 4 shows the head coefficient plotted versus cavitation number for the ambient (298 K) design flow rate condition [17]. The head coefficient remains constant at 0.22 until the cavitation number is lowered to 0.072. Thus, the critical cavitation number for this condition is 0.072. Figure 4 contains data from 3 separate tests, showing good repeatability.

Fast Fourier Transform (FFT) analysis and the cross-correlation of signals from two unsteady pressure transducers have been used to determine cavitation instability.
characteristics. Figure 5 shows the power spectral density plots of the unsteady pressure transducer signals for varying cavitation number [17]. Three dominant peaks at \( f/\Omega = 3.0 \) (A, \( \sigma > 0.072 \)), 1.14 (B, 0.053 < \( \sigma < 0.072 \)), and 1.0 (C, \( \sigma < 0.053 \)) are visible. According to Kim and Song [17], the peaks at \( f/\Omega = 3.0 \) (A), 1.14 (B), and 1.0 (C) correspond to blade passing, rotating cavitation, and asymmetric attached cavitation, respectively. Rotating cavitation results in uneven cavitating regions rotating at a speed faster (super-synchronous) than the inducer rotational speed in the same direction. When asymmetric attached cavitation occurs, the amplitude of asymmetric attached cavitation frequency increases and uneven cavitating regions attached to the blades rotate at the same (synchronous) speed as the inducer [1]. In the present study, the rotating cavitation onset cavitation number (\( \sigma_{RC} \)) is defined the cavitation number at which the amplitude of the rotating cavitation frequency increases to 5 times its steady state amplitude. Repeatability for the onset of rotating cavitation has been confirmed by 3 separate tests, and \( \sigma_{RC} \) is repeatable within the uncertainty.

**Non-dimensional Thermal Parameter Effects for Constant Reynolds Number** The test conditions for investigation of \( \Sigma^* \) effects are summarized in Table 2. \( \Sigma^* \) has been varied from 0.0229 to 1.59 while Re has been held constant at \( 4.15 \times 10^6 \). The value of \( \Sigma^* = 1.59 \) is similar to \( \Sigma^* = 1.81 \) of the KARI liquid oxygen (LOX) inducer under the actual operating conditions (87 K and 20,000 rpm).

Figure 6 presents the power spectral density plots of the inlet unsteady pressure fluctuations for \( \Sigma^* \) ranging from 0.0229 to 1.59 at \( \text{Re} = 4.15 \times 10^6 \). The magnitude of the rotating cavitation (peak B) at \( f/\Omega = 1.14 \) is decreased as \( \Sigma^* \) increases, and the arrows indicate \( \sigma_{RC} \). Figure 7 shows the \( \sigma_{RC} \) plotted versus \( \Sigma^* \). \( \sigma_{RC} \) is decreased by 21% as \( \Sigma^* \) increases from 0.0229 to 1.59. Flow visualization using a high speed camera qualitatively confirms this trend. Figure 8 (a) shows the cavitation region on an inducer blade for \( \Sigma^* = 0.0229 \), and Fig. 8 (b) shows the same blade for \( \Sigma^* = 1.59 \) at \( \sigma = 0.081 \) and \( \text{Re} = 4.15 \times 10^6 \). The cavitation region for \( \Sigma^* = 1.59 \) is visibly smaller than that for \( \Sigma^* = 0.0229 \). According to Horiguchi et al. [21], the rotating cavitation onset depends on the length of the cavitation region. Thus, the visualization data are consistent with the unsteady pressure data and confirm that increasing \( \Sigma^* \) suppresses rotating cavitation onset.

Ruggerie and Moore [4] defined the minimum cavitation number, \( \Sigma_{\text{min}} \), to explain the thermal effect on cavitation growth (Eq. (5)).

\[
\Sigma_{\text{min}} = \frac{p_m - p_{\text{atm}}}{\frac{1}{2}\rho U^2} = \sigma + \frac{p_m - p_{\text{atm}}}{\frac{1}{2}\rho U^2} = \sigma + \frac{\Delta p}{\frac{1}{2}\rho U^2} \tag{5}
\]
where \( p_{v,\text{min}} \) is the minimum vapor pressure within the cavitation bubble. The minimum cavitation number is the sum of the cavitation number (\( \sigma \)) and the vapor pressure depression (\( \Delta p_v \)) normalized by the dynamic head (\( \frac{1}{2} \rho U^2 \)). As \( \Sigma^* \) increases, the total heat needed for evaporation is increased, and the temperature within the cavitation bubble is decreased due to evaporation. As the temperature inside the cavitation bubble decreases, the vapor pressure within the cavitation bubble is decreased, increasing the vapor pressure depression (\( \Delta p_v \)) [2]. Consequently, the minimum cavitation number increases, and the cavitation bubble growth is suppressed. Thus, rotating cavitation onset occurs at a lower cavitation number as \( \Sigma^* \) increases.

Reynolds Number Effects for Constant Non-dimensional Thermal Parameter

Table 3 lists the test matrix for the investigation of Re effects. Figure 9 shows the power spectral density plots at Re = 2.30\( \times \)10^6 (Fig. 9 (a)) and 3.17\( \times \)10^6 (Fig. 9 (b)) for \( \Sigma^* = 0.0125 \). Figure 10 shows the corresponding data at Re = 4.81\( \times \)10^6 (Fig. 10 (a)) and 6.84\( \times \)10^6 (Fig. 10 (b)) for \( \Sigma^* = 1.26 \). The arrows indicate \( \sigma_{RC} \). For \( \Sigma^* = 0.0125 \), \( \sigma_{RC} \) (peak B) remains constant as Re increases, but, for \( \Sigma^* = 1.26 \), \( \sigma_{RC} \) is increased with increasing Re.

![Figure 7](image1.jpg)

**Figure 7.** The rotating cavitation onset cavitation number versus the non-dimensional thermal parameter at Re = 4.15\( \times \)10^6 (\( \phi/\phi_a = 1.0 \)).

![Figure 8](image2.jpg)

(a) \( \Sigma^* = 0.0227 \)  
(b) \( \Sigma^* = 1.55 \)

**Figure 8.** The inducer blade cavitation for different non-dimensional thermal parameter (\( \sigma = 0.081 \), \( \phi/\phi_a = 1.0 \), Re = 4.15\( \times \)10^6).

![Figure 9](image3.jpg)

(a) Re = 2.30 \( \times \) 10^6  
(b) Re = 3.17 \( \times \) 10^6

**Figure 9.** The power spectral density plots of unsteady pressure fluctuations at \( \Sigma^* = 0.0125 \) for different Reynolds number (\( \phi/\phi_a = 1.0 \)).

![Table 3](image4.jpg)

**Table 3.** Test conditions for Reynolds number effects tests.

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>Rotational speed [rpm]</th>
<th>Reynolds number</th>
<th>( \Sigma^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.3</td>
<td>4,500</td>
<td>2.30 ( \times ) 10^6</td>
<td>1.29 ( \times ) 10^2</td>
</tr>
<tr>
<td>25</td>
<td>4,900</td>
<td>2.50 ( \times ) 10^6</td>
<td>1.22 ( \times ) 10^2</td>
</tr>
<tr>
<td>27.5</td>
<td>5,800</td>
<td>3.17 ( \times ) 10^6</td>
<td>1.23 ( \times ) 10^2</td>
</tr>
<tr>
<td>37</td>
<td>4,150</td>
<td>2.76 ( \times ) 10^6</td>
<td>5.33 ( \times ) 10^-2</td>
</tr>
<tr>
<td>42</td>
<td>5,000</td>
<td>3.52 ( \times ) 10^6</td>
<td>5.38 ( \times ) 10^-2</td>
</tr>
<tr>
<td>45</td>
<td>5,700</td>
<td>4.16 ( \times ) 10^6</td>
<td>5.42 ( \times ) 10^-2</td>
</tr>
<tr>
<td>45</td>
<td>4,400</td>
<td>3.38 ( \times ) 10^6</td>
<td>1.04 ( \times ) 10^-1</td>
</tr>
<tr>
<td>48</td>
<td>5,200</td>
<td>3.99 ( \times ) 10^6</td>
<td>1.06 ( \times ) 10^-1</td>
</tr>
<tr>
<td>50</td>
<td>5,800</td>
<td>4.84 ( \times ) 10^6</td>
<td>1.08 ( \times ) 10^-1</td>
</tr>
<tr>
<td>55</td>
<td>4,350</td>
<td>3.93 ( \times ) 10^6</td>
<td>2.57 ( \times ) 10^-1</td>
</tr>
<tr>
<td>57.5</td>
<td>4,950</td>
<td>4.65 ( \times ) 10^6</td>
<td>2.57 ( \times ) 10^-1</td>
</tr>
<tr>
<td>60</td>
<td>4,700</td>
<td>5.55 ( \times ) 10^6</td>
<td>2.57 ( \times ) 10^-1</td>
</tr>
<tr>
<td>62</td>
<td>4,000</td>
<td>4.01 ( \times ) 10^6</td>
<td>5.15 ( \times ) 10^-1</td>
</tr>
<tr>
<td>64.5</td>
<td>5,550</td>
<td>4.73 ( \times ) 10^6</td>
<td>5.18 ( \times ) 10^-1</td>
</tr>
<tr>
<td>67</td>
<td>5,200</td>
<td>5.59 ( \times ) 10^6</td>
<td>5.16 ( \times ) 10^-1</td>
</tr>
<tr>
<td>68</td>
<td>5,450</td>
<td>5.94 ( \times ) 10^6</td>
<td>5.16 ( \times ) 10^-1</td>
</tr>
<tr>
<td>69</td>
<td>5,700</td>
<td>6.3 ( \times ) 10^6</td>
<td>5.20 ( \times ) 10^-1</td>
</tr>
<tr>
<td>73.5</td>
<td>4,100</td>
<td>4.68 ( \times ) 10^6</td>
<td>1.22</td>
</tr>
<tr>
<td>75</td>
<td>4,300</td>
<td>5.26 ( \times ) 10^6</td>
<td>1.26</td>
</tr>
<tr>
<td>77</td>
<td>4,700</td>
<td>5.74 ( \times ) 10^6</td>
<td>1.26</td>
</tr>
<tr>
<td>78.5</td>
<td>5,100</td>
<td>6.53 ( \times ) 10^6</td>
<td>1.26</td>
</tr>
<tr>
<td>80</td>
<td>5,400</td>
<td>6.85 ( \times ) 10^6</td>
<td>1.27</td>
</tr>
</tbody>
</table>
The dependence of $\sigma_{RC}$ on $Re$ for various values of $\Sigma^*$ is presented in Fig. 11. For $\Sigma^* = 0.0125$, $\sigma_{RC}$ is independent of $Re$. For $\Sigma^* \geq 0.0537$, $\sigma_{RC}$ increases with $Re$, and such $Re$ effects (e.g. $\frac{\partial (\sigma_{RC})}{\partial (Re)}$) become stronger with increasing $\Sigma^*$. Visualization of the inducer blade cavitation qualitatively confirms such $Re$ effects. Figure 12 shows the inducer blade cavitation at $Re = 2.30 \times 10^6$ (Fig. 12 (a)) and $3.17 \times 10^6$ (Fig. 12 (b)) for $\Sigma^* = 0.0125$. For $\Sigma^* = 0.0125$, the length of inducer blade cavitation region is not affected by the $Re$ change. For low $\Sigma^*$, where the thermal effect is negligible [19], the vapor depression is also negligible ($\Delta p_v \approx 0$). Therefore, the minimum cavitation (Eq. (5)) and $\sigma_{RC}$ are insensitive to $Re$ for low $\Sigma^*$.

Figure 13 shows the inducer blade cavitation for $\Sigma^* = 1.26$ at $Re = 4.81 \times 10^6$ (Fig. 13 (a)) and $6.84 \times 10^6$ (Fig. 13 (b)). For $\Sigma^* = 1.26$, the length of the inducer blade cavitation region at $Re = 6.84 \times 10^6$ is visibly longer than that of $Re = 4.81 \times 10^6$. Thus, the rotating cavitation onset depends on $Re$ at $\Sigma^* = 1.26$. Tokumasu et al. [22] performed a numerical analysis of $Re$ effects on cavitation growth for a hydrofoil. They found that the cavitation region is bigger at a higher $Re$ in liquid oxygen in which the thermal effect is significant. At high $\Sigma^*$ and high $Re$, the vapor pressure depression ($\Delta p_v$) and dynamic head ($\frac{1}{2} \rho U^2$) in Eq. (5) are both large. On the other hand, at high $\Sigma^*$ and low $Re$, the dynamic head is smaller; therefore, the minimum cavitation number is larger. Thus, for high $\Sigma^*$, the cavitation region growth is promoted as $Re$ increases, and the rotating cavitation onset occurs at a higher cavitation number.

**Combined Effects of Reynolds Number and Non-dimensional Thermal Parameter**

Figure 14 shows the plot of $\sigma_{RC}$ versus $\Sigma^*$ for $Re = 4.15 \times 10^6$ as well as that for $N = 5,000$ rpm from Kim and Song [17]. In [17], experiments had been performed by varying the water temperature while maintaining a constant rotational speed of 5,000 rpm. Thus, $Re$ increased from $2.6 \times 10^6$ to $6.4 \times 10^6$ simultaneously as $\Sigma^*$ increased from 0.0116 to 1.80. In Fig. 14, $\sigma_{RC}$ becomes independent of $\Sigma^*$ for $\Sigma^* > 0.54$ for $N = 5,000$ rpm [17]. On the other hand, $\sigma_{RC}$ continues to decrease for $\Sigma^* > 0.54$ for...
Figure 14. The rotating cavitation onset cavitation number versus the non-dimensional thermal parameter comparing with the Re=4.15×10⁶ and N=5,000 rpm [17] at Φ/Φ₀=1.0.

Re = 4.15×10⁶. For the N = 5,000 rpm study, the cavitation suppression effects due to the increase in Σ⁺ and the cavitation promotion effects due to the increase in Re occur simultaneously. For Σ’ < 0.54, where the effects of Re is weaker, σRC is decreased as Σ⁺ increases. However, as Σ⁺ increases further, the Re effects becomes stronger, essentially cancelling out the Σ⁺ effects. Thus, σRC becomes “seemingly” independent of Σ⁺ for 0.54 < Σ⁺ < 1.80 when N = 5,000 rpm.

Conclusions

The effects of non-dimensional thermal parameter (Σ⁺) and Reynolds number (Re) on rotating cavitation onset for a turbopump inducer have been measured in water and explained. The new conclusions from this study are:

1. The non-dimensional thermal parameter (Σ⁺) and Reynolds number (Re) have significant effects on rotating cavitation onset.

2. Increasing the non-dimensional thermal parameter (Σ⁺) at a given constant Reynolds number (Re) lowers the rotating cavitation onset cavitation number (σRC).

3. For the tested inducer, the rotating cavitation onset cavitation number (σRC) is increased as the Reynolds number (Re) increases for Σ⁺ higher than 0.0537. On the other hand, for Σ⁺ lower than 0.0125, the rotating cavitation onset is independent of the Reynolds number (Re).

4. When the liquid temperature increases and the inducer rotational velocity remains constant, increasing non-dimensional thermal parameter (Σ⁺) suppresses cavitation and increases Reynolds number (Re) promotes cavitation, counteracting each other.

5. Consideration of fluid thermal properties and inducer size and speed (Σ⁺) is insufficient to explain cavitation instability onset. In addition, fluid viscosity (Re) has to be considered.

NOMENCLATURE

A area of an inducer inlet
c Φ tip clearance
Cp pressure coefficient = (p∞₀ − p)/½pΩ²
C L characteristic length of inducer
Cp_l liquid heat capacity
D diameter of inducer
DB rΩ²/Σ [16]
Δψ unsteady pressure fluctuation coefficient
ψ head coefficient, = (p₂ − p₁)/½pΩ²
ψ₀ Head coefficient without cavitation
Σ⁺ non-dimensional thermodynamic parameter
Ω rotational frequency (Hz)

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