Measurement of Temperature Effects on Cavitation in a Turbopump Inducer

Temperature effects on the critical cavitation number and rotating cavitation in a turbopump inducer have been experimentally investigated in water. Static pressures upstream and downstream of the inducer have been measured to determine the cavitation performance, and cavitation instabilities have been detected using unsteady pressure sensors and a high-speed camera. Two kinds of cavitation instabilities have been identified—rotating cavitation and asymmetric attached cavitation. To quantify temperature effects, nondimensional thermal parameter has been adopted. Increasing water temperature, or increasing nondimensional thermal parameter, lowers the critical cavitation number. Increasing nondimensional thermal parameter also shifts the onset of rotating cavitation to a lower cavitation number and reduces the intensity of rotating cavitation. However, for values larger than 0.540 (340 K, 5000 rpm), the critical cavitation number and the rotating cavitation onset cavitation number become independent of the nondimensional thermal parameter. The onset of the head coefficient degradation correlates with the onset of rotating cavitation regardless of temperature. [DOI: 10.1115/1.4030842]

Introduction

In liquid rocket engines, turbopumps are used to pump liquid fuel and oxidizer into the combustor. To minimize size and weight, turbopumps rotate at high-speeds, and this requirement leads inevitably to cavitation. Therefore, axial inducers have been installed to prevent impeller cavitation. Yet, the inducer itself can suffer from cavitation, leading to performance degradation and cavitation instabilities.

Cavitation instabilities can be broadly categorized into rotating cavitation, asymmetric attached cavitation, and cavitation surge. Rotating cavitation is a local cavitation instability in which the cavitation region propagates at either subsynchronous or (sometimes) subsynchronous speed in the direction of the inducer rotation. In asymmetric attached cavitation, the cavitation region (attached to the blade) rotates at the same speed as the inducer. Cavitation surge is a system instability, where the flow oscillates with subsynchronous frequency in the axial direction.

Kamijo et al. [1] experimentally examined the rotating cavitation with unsteady pressure transducers and cavitation visualization. Tsujimoto et al. [2] identified detailed characteristics of cavitation instabilities, including the propagation speed, cell number, and dependency on the rotational speed and piping system. Recently, Fujii et al. [3] and Tsujimoto and Semenov [4] found new types of cavitation instabilities, such as higher-order rotating cavitation and higher-order cavitation surge. These instabilities have similar characteristics with the conventional rotating cavitation and cavitation surge, but they occur at higher frequencies than the conventional cavitation instabilities. Due to their higher frequencies, they may cause resonance of the inducer blades.

Cavitation is sensitive to liquid temperature. According to Brennen [5], cavitation growth is suppressed as the liquid temperature increases, and this phenomenon is called temperature effects. At higher liquid temperatures, the evaporation rate for the same bubble volume is larger than at lower temperatures. Therefore, at higher liquid temperatures, the total heat needed for evaporation at the bubble interface and the temperature drop within the

bubble (due to evaporation) are both larger. Inside the bubble, as the temperature decreases, the vapor pressure also decreases. Thus, the “effective” cavitation number is increased, and the cavitation growth is delayed as the liquid temperature increases.

Stepanoff [6] used the B-factor, or the ratio of the vapor volume to the liquid volume in the vaporization process, to represent the temperature effects of liquids and adjust the difference in cavitation performance between water and other liquids. Brennen [5] suggested the thermal parameter, \( \Sigma \) (m/s^3/2), from heat transfer analysis of cavity bubble growth. This parameter represents the rate of energy transfer from the liquid to the vapor

\[
\Sigma = \frac{(\rho L)^2}{p^2 C_{pl} T \sqrt{\eta}}
\]

(1)

Subsequently, Franc et al. [7] derived a nondimensional thermal parameter \( \Sigma^* \)

\[
\Sigma^* = \Sigma \sqrt{C/U^3}
\]

(2)

The nondimensional thermal parameter (\( \Sigma^* \)) considers the characteristic length of the pump (\( C \)) and reference velocity (\( U \)). As the temperature of the working fluid increases, the nondimensional thermal parameter also increases.

Ruggeri and Moore [8] measured cavitation performance in an inducer with various liquids and temperatures, and suggested an empirical correlation for temperature effects on cavitation performance. Franc et al. [9] measured leading edge cavity length by visualization in an inducer at different temperatures with refrigerant R-114 as the working fluid. Cavity length and onset cavitation number of alternate blade cavitation and rotating cavitation all decreased as the temperature increased. Yoshida et al. [10] found that increasing the liquid nitrogen temperature slowed down the growth rate of cavity length of inducer tip cavitation and lowered the onset cavitation number of asymmetric attached cavitation. Kikuta et al. [11] found that cavitation surge occurred in water at 296 K (\( \Sigma^* \approx 0.01 \)), whereas cavitation surge did not occur in liquid nitrogen at 76 K (\( \Sigma^* \approx 7 \)). Yoshida et al. [12,13] found that: 1) increasing temperature suppressed the onset of both rotating and asymmetric attached cavitation; 2) the rotating cavitation occurred at the same cavity length regardless of temperature; and
3) increasing temperature weakened the intensity of asymmetric attached cavitation. Kikuta et al. [14] performed experiments in liquid nitrogen to measure the influence of rotational speed on temperature effects. Cavity length was suppressed as nondimensional thermal parameter was increased by lowering the rotational speed at a given temperature.

The temperature effects on cavitation inducer in water have also been investigated. Cervone et al. [15] conducted experiments on the influence of water temperature on cavitation instabilities in a three-bladed inducer. They found that: 1) the intensity of cavitation surge was weaker at higher temperatures (343 K) than at lower temperatures (297 K) and 2) increasing temperature did not change either frequency or type of cavitation instabilities. Torre et al. [16] found that the critical cavitation number\(^1\) was higher when the water temperature is lower. On the other hand, the breakdown cavitation number\(^2\) was not affected by the increasing water temperature. They also found that the onset of asymmetric attached cavitation corresponded to the critical cavitation number. However, they did not show a clear relationship between the critical cavitation number and water temperatures, and how temperature change affects the rotating cavitation.

In addition, analytical and numerical studies have been performed to investigate the temperature effects. Cooper [17] developed an analytical model for temperature effects on inducer cavitation performance using the B-factor. Watanabe et al. [18] developed an analytical model to simulate the temperature effects using singularity analysis to investigate the cavitation in an inducer cascade. They suggested the nondimensional thermal parameter, \(\Sigma^*\), in a different way. They found that: 1) as \(\Sigma^*\) increases, the onset cavitation number of cavitation instabilities moved toward lower cavitation number [19] and 2) temperature effects were more significant at higher temperatures, and temperature effects became larger as the cavitation bubble becomes longer due to the need of larger latent heat [20]. Tokumasu et al. [21] performed a numerical simulation of a two-dimensional hydrofoil and found that the size of cavitation was smaller and temperature drop was smaller at a higher temperature liquid oxygen. Hosangadi and Ahuja [22] numerically simulated the cavitation hydrofoil in liquid hydrogen and liquid nitrogen. The amount of temperature drop was similar at different temperatures, and temperature drop increased as freestream velocity increased. Hosangadi et al. [23] also performed numerical simulations using their CFD code for liquid hydrogen and water in cavitation inducer. They found that the temperature drop in hydrogen fluid was about 0.5–1.0 K for reference temperature of 20.55 K. Gonzales et al. [24] performed a numerical simulation of inducer cavitation in liquid hydrogen at different temperatures. They found that cooling effect due to cavitation was lower than heating effect due to viscosity.

Despite such efforts, the effects of water temperature on the rotating cavitation onset and intensity have not yet been investigated. Therefore, the present study provides detailed measurements of cavitation performance and cavitation instabilities in a turbopump inducer at varying water temperatures. The nondimensional thermal parameter is employed to compare with cryogenic conditions. The specific research questions of the present study are as follows:

1. How does water temperature affect inducer cavitation performance and critical cavitation number?
2. Do the characteristics of inducer cavitation instabilities change with water temperature?

**Experimental Facility and Procedures**

Figure 1 shows a schematic of the turbopump inducer test facility at Seoul National University. The closed-loop facility is composed of a water tank, rotating parts, a flow meter, a control valve, and a booster pump. It has been designed for turbopump inducer testing in water under cavitating and noncavitation conditions. Rotating parts include the test inducer, shaft, and motor. Filtered water is kept in a 0.9 m\(^3\) stainless water tank, and the pressure is controlled with either a vacuum pump or compressed air in the water tank. A 20-kW electrical heater has been installed in the water tank to adjust the water temperature. The inlet of the water tank is curved to add swirl and remove bubbles in the water. The flow is driven by a 60-kW motor with a maximum rotational speed of 10,000 rpm. The rotational speed is controlled to within 0.02% by a variable frequency drive.

Water from the tank flows through the inducer and the collector. Downstream of the collector, a flow straightener is installed at ten pipe diameters upstream of the flow meter. The globe control valve, which deters cavitation occurrence, is used to control the flow rate. When severe cavitation occurs, the head coefficient drops drastically, and water does not flow at the given flow rate. Therefore, an additional pump (booster pump) has been installed to force the flow through the test facility during cavitating condition. Elastic couplings have been installed at the exits of the inducer and collector.

Figure 2 is the test inducer designed by the Korea Aerospace Research Institute (KARI), and its specifications are summarized in Table 1. The inducer has high solidity and moderate blade tip angle at the inlet [25].

In this study, the inducer rotational speed has been fixed to be 5000 rpm ± 1 rpm. The mean flow rate has been measured downstream of the inducer using an electromagnetic flow meter with an accuracy of 0.25% full scale (20 kg/s). Figure 3 shows the schematic of the test section. Eight and four static pressure transducers with an accuracy of 0.04% full scale (200 kPa \(P_1\)) and 400 kPa \(P_2\)) have been installed at \(x/D = -1.0 (P_1)\) and \(x/D = 0.75 D (P_2)\) from the inducer tip leading edge to measure the inducer static head coefficient. Eight unsteady pressure transducers with an accuracy of 0.1% full scale (350 kPa) have been installed \(x/D = -0.25\) to identify cavitation instabilities. A frequency response of the unsteady pressure transducers is 400 kHz. During the experiments, unsteady pressure signal acquisition rate is 50 kHz and it has been received during 1 s for each measurement point. The flow rate has been fixed at the design flow rate.

![Fig. 1 Seoul National University turbopump inducer experimental facility](image-url)
throughout the experiment. The uncertainty of each parameter with 95% confidence interval is as follows: ±0.00398 in $w$, ±0.000422 in $T$, and ±0.000759 in $r$.

Experimental Results and Discussion

Test Inducer Characteristics. Noncavitating suction performance has been measured at 298 K ($\Sigma^* = 0.0116$), as shown in Fig. 4. The inducer characteristic has a negative slope for flow coefficient values above 0.0456. For flow coefficient values below 0.0456, the inducer characteristic has a zero or positive slope. At the design flow rate ($\phi_a = 0.096$), the measured head coefficient is 0.215, equivalent to the design value. Three repeatability tests have been performed. The head coefficient is repeatable to within 0.75% at the design flow coefficient of $\phi_a = 0.096$. At the design point, the Reynolds number is $2.58 \times 10^6$ based on the tip radius, rotational velocity, and fluid viscosity.

Figure 5 shows the cavitation performance at 298 K and the design flow coefficient. For cavitation number from 0.3 to 0.0702, head coefficient remains constant at 0.215. For cavitation number lower than 0.0702, the head coefficient is decreased. Thus, the critical cavitation number for this case is 0.0702. Repeatability has been confirmed by three separate experiments showing similar values and trends.

Cavitation Instabilities. Cavitation instabilities at the design flow rate have been identified. Fast Fourier transform analysis has been used to determine the frequency of the instability. The nature of the instability and the number of rotating instability cells have been determined from the cross-correlation of signals from two unsteady pressure transducers. For axial instabilities, the phase of

![Fig. 2 Test inducer](image)

![Fig. 4 Noncavitating performance curves at 298 K ($\Sigma^* = 0.0116$)](image)

![Fig. 3 Test section showing the locations of static and unsteady pressure transducers](image)

![Fig. 5 Repeatability test for cavitation performance ($\phi_a = 0.096$ and $T = 298 \text{K} \left(\Sigma^* = 0.0116\right)$)](image)

![Fig. 6 The power spectral density of inducer inlet pressure fluctuations ($\phi_a = 0.096$ and $\Sigma^* = 0.0116 \left(T = 298 \text{K}\right)$)](image)
the cross-correlation between the two unsteady pressure signals is equal to 0 deg. For rotating instabilities, the ratio of the phase of the cross-correlation ($\varphi$) and the angular distance between the pressure transducers ($\Delta \theta$) are equal to the number of the rotating cells ($n_{cell}$)

$$n_{cell} = \frac{\varphi}{\Delta \theta}$$  \hspace{1cm} (3)

The frequency of instability ($f_i$) is then determined by dividing the detected frequency ($f_d$) by the rotating cell number ($n_{cell}$)

$$f_i = \frac{f_d}{n_{cell}}$$  \hspace{1cm} (4)

Two kinds of cavitation instabilities have been identified in the test inducer at the design flow rate. Figure 6 shows the power spectral density peaks from one unsteady pressure transducers corresponding to $f/\Omega = 3.0$ (A), 1.14 (B), and 1.0 (C), where $f/\Omega = 3.0$ is the blade passing frequency. For $\sigma > 0.071$, the peak at $f/\Omega = 3.0$ (A) is dominant due to blade passing and symmetric cavitation (Fig. 7). For $0.053 < \sigma < 0.071$, the dominant peak exists at $f/\Omega = 1.14$ (B). Finally, for $\sigma < 0.053$, $f/\Omega = 1.0$ is the dominant peak (C). To determine the type of instability occurring at $f/\Omega = 1.14$ and 1.0, the power spectral density, phase, and coherence analysis have been performed using cross-correlation of signals from two adjacent unsteady pressure transducers ($\Delta \theta = 45$ deg) at $\sigma = 0.068$ and 0.046 (Figs. 8 and 9), respectively. Peak B propagates at a supersynchronous speed ($f/\Omega = 1.14$). The phase difference between the two transducer signals is 45 deg at the same frequency with a value of coherence near unity (Fig. 8). Therefore, peak B represents rotating cavitation instability which has been previously identified [1,2]. Peak C propagates at the synchronous speed ($f/\Omega = 1.0$). In Fig. 9, there is a peak at the rotational frequency, and, at this frequency, the phase difference of the two transducer signals is 45 deg with a coherence near unity. This result indicates asymmetric cavitation, which is visualized in Fig. 10. Figure 10 shows one rotation of the inducer at $\sigma = 0.047$, where asymmetric attached cavitation occurs. There are one shorter cavity (1) and two longer cavities (2 and 3) attached to the inducer blades. Thus, peak C is asymmetric attached cavitation rotating at the synchronous speed [2,26].

Figure 11 shows the plots of the mean head coefficient and the amplitude of the head coefficient fluctuation at the frequency of rotating cavitation versus the cavitation number at 298 K ($\Sigma^* = 0.0116$) and design flow rate. The critical cavitation number ($\sigma_{crit} = 0.070$) corresponds to the beginning of the rise of the head coefficient fluctuation amplitude at the rotating cavitation

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**Fig. 7** High-speed images of symmetric cavitation. Same length cavities are attached to blade rotating synchronous speed with the inducer ($\sigma = 0.12$, $\phi_a = 0.096$, and $\Sigma^* = 0.0116$ ($T = 298$ K)).

**Fig. 8** The power spectral density, phase difference, and coherence of unsteady pressure fluctuations from two pressure transducers with 45 deg angular separation in upstream of the inducer ($\sigma = 0.068$, $\phi_a = 0.096$, and $\Sigma^* = 0.0116$ ($T = 298$ K)).

**Fig. 9** The power spectral density, phase difference, and coherence of unsteady pressure fluctuations from two pressure transducers with 45 deg angular separation in upstream of the inducer ($\sigma = 0.046$, $\phi_a = 0.096$, and $\Sigma^* = 0.0116$ ($T = 298$ K)).
cryogenic conditions in terms of

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298 K). 

328 K, 340 K, and 357 K, and the corresponding nondimensional thermal parameters ($\Sigma'$) are listed in Table 2. In this paper, the inducer radius (0.047 m) and tip velocity (24.7 m/s) are the characteristic length and reference velocity. As water temperature increases, $\Sigma'$ is increased, and $\Sigma'$ value at 357 K is equivalent to $\Sigma'$ of liquid oxygen (LOX) at cryogenic conditions. Thus, for this inducer, when the water temperature is above 357 K, cryogenic conditions in terms of $\Sigma'$ can be simulated.

Table 2 Test temperatures and thermal parameter values

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Rotational speed (rpm)</th>
<th>$\Sigma$ (m/s$^{3/2}$)</th>
<th>$\Sigma'$ = $\Sigma$/C/$U^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water 298</td>
<td>5000</td>
<td>6.55</td>
<td>1.16 x 10^{-2}</td>
</tr>
<tr>
<td>313</td>
<td>5000</td>
<td>3.03 x 10^{1}</td>
<td>5.39 x 10^{-2}</td>
</tr>
<tr>
<td>328</td>
<td>5000</td>
<td>1.14 x 10^{2}</td>
<td>2.04 x 10^{-1}</td>
</tr>
<tr>
<td>340</td>
<td>5000</td>
<td>3.03 x 10^{2}</td>
<td>5.40 x 10^{-1}</td>
</tr>
<tr>
<td>357</td>
<td>5000</td>
<td>1.01 x 10^{3}</td>
<td>1.80</td>
</tr>
<tr>
<td>LOX 87</td>
<td>20,000</td>
<td>8.15 x 10^{3}</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Figure 12 shows plots of the head coefficient versus cavitation number for various values of $\Sigma'$. Arrows show the critical cavitation number for each $\Sigma'$ value. The critical cavitation number decreases as $\Sigma'$ increases. However, for cavitation numbers lower than the critical cavitation number, the head coefficient is independent of $\Sigma'$. The sensitivity of cavitation instability to $\Sigma'$ also has been investigated. Figure 13 presents the power spectral density for $\Sigma'$ from 0.0539 to 1.80. The trend of dominant peak transition from $f/\Omega = 3.0$ to 1.0 remains the same, despite $\Sigma'$ variations. The onset cavitation number and amplitude of unsteady pressure fluctuation of rotating cavitation (B) are decreased as $\Sigma'$ increases, whereas the asymmetric attached cavitation (C) is insensitive to $\Sigma'$ variations.

The dependence of the critical cavitation number and the rotating cavitation onset on $\Sigma'$ is clearly shown in Fig. 14. For $\Sigma'$ from 0.0116 to 0.540, the critical cavitation number is decreased by 15%. For $\Sigma'$ from 0.540 to 1.80 (equivalent to the cryogenic condition), the critical cavitation number is independent of $\Sigma'$. Therefore, similarity with cryogenic conditions in terms of $\Sigma'$ can be achieved with inducer water testing for $\Sigma' > 0.540$.

Figure 14 also shows that the rotating cavitation onset cavitation number decreases by 15% as $\Sigma'$ increases from 0.0116 to 0.540. As also indicated by Horiguchi et al. [27], the rotating cavitation starts to occur when the cavity length reaches about 65% of the blade spacing. Yoshida et al. [12] also confirmed that cavity length is shorter at the high $\Sigma'$ than at the low $\Sigma'$ at same cavitation number. Thus, the cavitation number for the onset of rotating cavitation shifts to lower values at high $\Sigma'$. Therefore, the onset of rotating cavitation is delayed as $\Sigma'$ increases. On the other hand, for $\Sigma'$ from 0.540 to 1.80, the onset cavitation number of rotating cavitation is independent of $\Sigma'$. Figure 14 also shows that the cavitation number corresponding to the onset of rotating cavitation correlates well with the critical cavitation number at all
values of $\Sigma^*$, Thus, onset of the rotating cavitation leads to the onset of the head coefficient degradation regardless of $\Sigma^*$ variations.

Conclusions

The influence of water temperature on the critical cavitation number and cavitation instability onset for a turbopump inducer has been experimentally investigated for $\Sigma^*$ from 0.0116 to 1.80. The following are the new conclusions from the investigation:

1. At the rotational speed of 5000 rpm, the value of $\Sigma^*$ in the cryogenic conditions under LOX operation can be achieved in water tests when flow temperature is above 357 K.
2. The onset of rotating cavitation correlates with the head coefficient degradation regardless of $\Sigma^*$ variations.
3. For $\Sigma^*$ below 0.540 (340 K), as $\Sigma^*$ increases, the amplitude of the rotating cavitation peak oscillations is diminished and the onset cavitation number of the rotating cavitation is decreased. Thus, increasing $\Sigma^*$ enhances the hydrodynamic stability of the test inducer by suppressing the rotating cavitation.
4. For $\Sigma^*$ from 0.540 to 1.80 (340–357 K), the cavitation number corresponding to the onset of rotating cavitation remains constant.
5. The critical cavitation number trends are similar to the trends of cavitation number for the onset of rotating cavitation at all values of $\Sigma^*$.

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Nomenclature

- $A$: area of an inducer inlet (m$^2$)
- $C$: characteristic length of pump
- $C_p$: liquid heat capacity
- $D$: diameter of inducer
- $f$: frequency (Hz)
- $f_d$: detected frequency (Hz)
- $f_r$: real frequency of instability (Hz)
- $L$: latent heat
- $n_{cell}$: number of rotating cells
- $Q$: flow rate
- $r$: inducer inlet radius
- $t$: tip clearance
- $T$: time
- $T_\infty$: flow temperature
- $U$: tip rotational speed
- $\alpha$: thermal diffusivity of liquid
- $\Delta \psi$: unsteady pressure fluctuation coefficient (peak-to-peak)
- $\theta$: angular distance (deg)
- $\rho_v$: vapor density
- $\rho_l$: liquid density
- $\sigma$: cavitation number, $\sigma = (\rho_1 - \rho_v) / [(1/2)\rho r^2\Omega^2]$
- $\tau$: period for one rotation
- $\psi$: phase of the cross-correlation
- $\phi$: flow coefficient, $\phi = Q / Ar\Omega$
- $\psi$: head coefficient, $\psi = (p_2 - p_1) / [(1/2)\rho r^2\Omega^2]$
- $\Omega$: Inducer rotational speed, rotational frequency (Hz)
- $\Sigma$: thermodynamic function
- $\Sigma^*$: nondimensional thermodynamic parameter

References


