Experimental Study of Thermodynamic Effect of Tip Leakage Cavitation in Hot Water

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Abstract

Thermodynamic effect on cavitation appears in cryogenic fluids. The thermodynamic effect is considered to suppress the development of cavitation. The cavitation performance of inducer of liquid rocket turbopump with liquid hydrogen and oxygen is improved by the thermodynamic effect. The authors have conducted experimental studies about thermodynamic effect on cavitation around single hydrofoils in hot water in previous study, where sheet cavity and sheet/cloud cavity occurs. However, cavitation in inducer is not sheet cavity which is separation type but tip leakage cavity which is vortex type. Therefore, in the present study, experiment is conducted about tip leakage cavitation in order to clarify the intensity thermodynamic effect on vortex type cavitation. In the present study, cavitation experiments is conducted with high temperature and high pressure cavitation tunnel, NACA 0009 hydrofoil is chosen for a test body. In the experimental results, development of the pattern of the tip leakage cavitation did not change by the change of freestream temperature from room temperature up to 90 ºC. The result of sheet cavitation is in our previous study. The effect of freestream temperature on a temperature reduction inside the cavity is investigated by the direct measurement technique of temperature inside the tip leakage cavity.

Keywords

Tip Leakage Cavitation, Hot Water, NACA0009, Temperature Measurement, Thermistor

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INTRODUCTION

Cavitation occurs when the pressure of fluid is decreased roughly below the saturated vapor pressure. The occurrence of cavitation deteriorates the performance of inducer of liquid propellant rocket turbopump with liquid hydrogen and oxygen. So, influence of cavitation cannot be neglected in the design of inducer of liquid propellant rocket turbopump and to understand the behavior of cavitation is necessary. A number of cavitation studies have been conducted for cavitation in room temperature. However, when working fluid is replaced to cryogenic fluid, the behavior of cavitation is different from that of cavitation in room temperature water. Latent heat to be supplied from liquid around cavity is needed for vaporization, and temperature of liquid around cavity is decreased. As a result, local saturated vapor pressure is decreased and the growth of cavity is suppressed. Thus, the performance of inducer of liquid propellant rocket turbopump is improved by the thermodynamic effect. This suppression of cavity growth and improvement of performance of inducer are called thermodynamic effect. Thermodynamic effect on cavitation in water of room temperature is negligibly small, on the other hand, that in cryogenic fluids or hot water or refrigerant becomes significant and cannot be neglected, which is usually utilized in a condition near the critical temperature. The extent of thermodynamic effect is known to increasing temperature of working fluid, however, Cervone et al. reported diverse behavior of cavitation in hot water of 70 ºC, the occurrence of cloud cavitation and super cavitation shifts toward higher cavitation number compared to water of 25 ºC [1]. The result indicates that the intensity of thermodynamic effect is still unclear, and that is considered to depend not only on thermal property of the fluid but also on cavitation pattern or the unsteadiness.

The authors conducted experimental studies about thermodynamic effect on cavitation around single hydrofoils in hot water [2], where sheet cavity and sheet/cloud cavity occurs. However, cavitation in inducer is not sheet cavity which is separation type but tip leakage cavity which is vortex type. Also, an author conducted experiments using room temperature water and numerical calculation in order to clarify the mechanism of cavitation instabilities in real inducer [3]. According to the study, there was close interaction between tip leakage cavitation and cavitation instabilities. Therefore, in the present study, the cavity types in leakage flow and temperature depression inside the tip leakage cavity are experimentally observed in order to clarify the intensity of thermodynamic effect on vortex type cavitation. The experiment was conducted with NACA0009 hydrofoil with tip clearance, and temperature of cavity was measured by using thermistor probe.

1. THERMODYNAMIC EFFECT

The thermodynamic parameter Σ proposed by Brennen [4] is defined as,

$$\Sigma = \frac{L^2 \rho_v^{\ 2}}{\rho_l^{\ 2} c_{pl} T_\infty \alpha_l^{\ 1/2}} \tag{1}$$

where L is latent heat of liquid, ρ_v is density of vapor, ρ_l is density of liquid, c_{pl} is heat capacity of liquid, T_∞ is temperature of free stream and α_l is thermal diffusivity of liquid. This parameter is considerd to describe the cause of thermodynamic effect, but the result of cavity volume reduction on each hydraulic machinery is still unclear as mentioned before. To investigate the incidence of thermodynamic effect, many experimental research had been conducted. Franc et al. investigated a cavitating inducer in R114 and estimate the temperature depression in cavity by comparing the experimental results of cavitating inducer in room temperature water [5]. Niiyama et al. visualized cavitation hydrofoil in liquid Nitrogen and measure temperature depression in the cavity [6]. Many experimental research of thermodynamic effect were conducted using cryogenic fluids or refrigerant as working fluid. However, the experimental results conducted in these fluids cannot be directly compared with the results obtained in room temperature water because it may includes the influence of the difference of fluid. Therefore, in order to conduct cavitation experiments with and without thermodynamic effect in same fluid, high temperature and high pressure cavitation tunnel had been used in present study. The working fluids of this tunnel is water and the free stream temperature can be varied from room temperature to 140 ºC, in which the thermodynamic parameter Σ can be varied for wide range.

In present study, water is used as working fluid and by varying temperature of water the thermodynamic effect on tip leakage cavitation is investigated. Figure 1 shows thermodynamic parameter Σ of some cryogenic fluids, refrigerant and water. Thermodynamic parameter Σ of room temperature is in the order of 10^0 and the extent of thermodynamic effect on cavitation is too small to observe at that temperature. By increasing temperature of water, thermodynamic parameter increases. At the temperature about 140 ºC the value of Σ reaches the order of 10^4, this value is corresponding to Σ of Liquids Nitrogen. By increasing temperature of water, water can simulate cryogenic fluids such as Liquid Nitrogen and Liquid Oxygen in the aspect of thermodynamic parameter. Also water show wide range of Σ, this enables to study cavitation with and without thermodynamic effect by using same fluid. In this study, a cavitation tunnel which can vary temperature of water from room temperature to 140 ºC had been constructed.

2. EXPERIMENTAL SET UP

Cavitation tunnel was constructed to conduct cavitation experiment of high temperature and high pressure water. The overview of this tunnel is shown in Fig 2. This tunnel is made of stainless steel. The geometry of flow channel is 30 mm ×

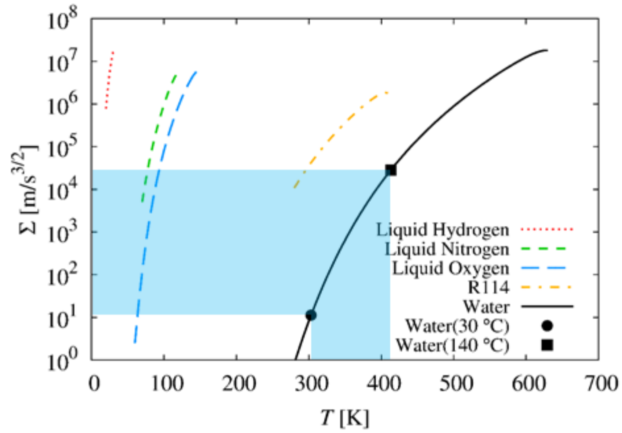


Figure 1. Thermodynamic parameter Σ of some cryogenic fluids, R114 and water

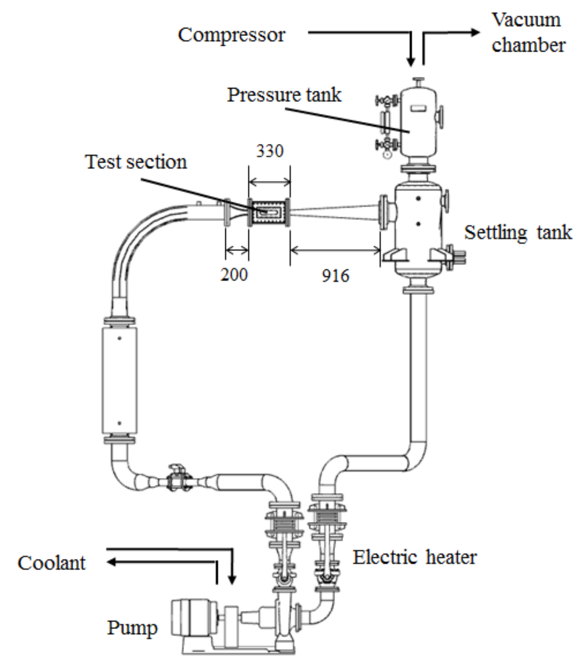


Figure 2. Overview of high temperature and high pressure water cavitation tunnel

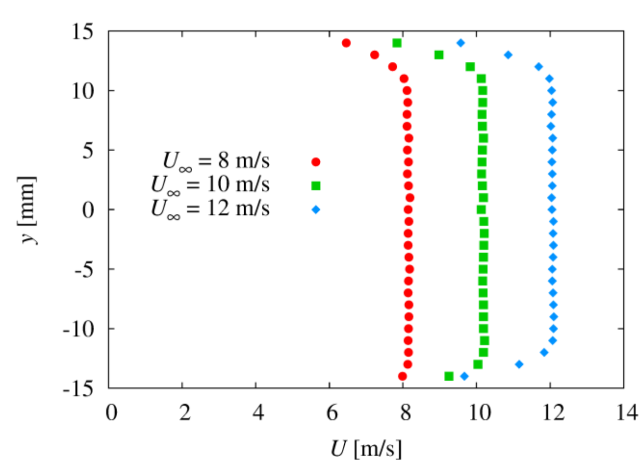
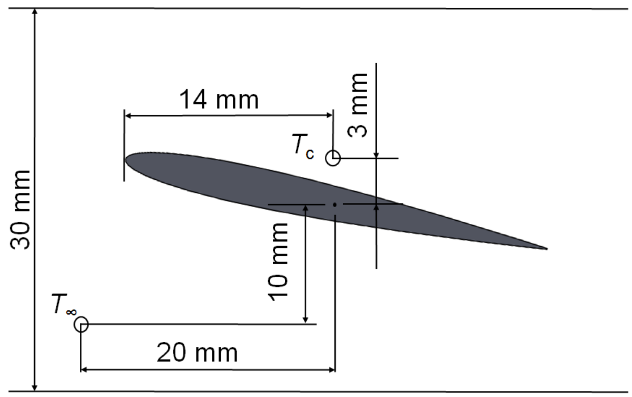
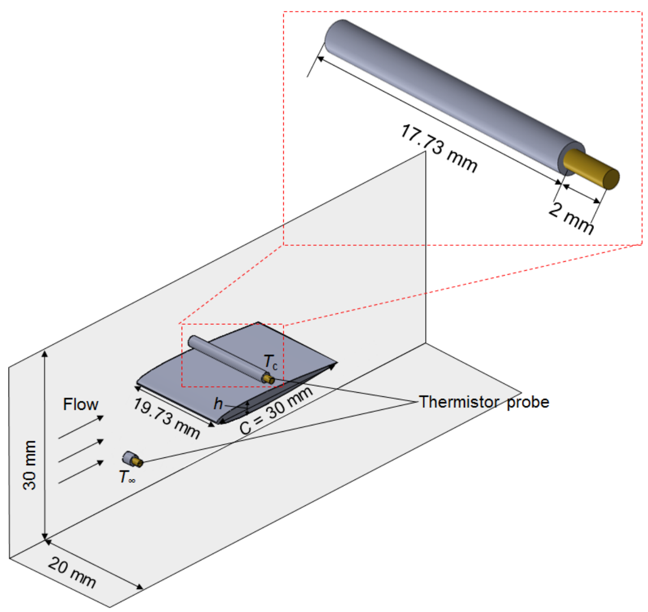


Figure 3. Vertical distribution of streamwise velocity



(a) Side view



(b) Perspective view

Figure 4. Configulation of temperature probe and NACA0009 hydrofoil (chord length 30 mm, angle of attack 12 deg)

Table 1. Experimental conditions, corresponding thermodynamic parameter and Reynolds number

AoA [deg]	12			
U_∞ [m/s]	10			
T_∞ [℃]	30	70	80	90
Σ [m/s$^{3/2}$]	11.3	387.4	809.1	1610.6
Re	3.8×10^5	7.3×10^5	8.2×10^5	9.2×10^5

20 mm in cross section and length is 330 mm. The window of glass enables end-view visualization of cavitation appearance. This tunnel can vary the temperature of water up to 140 ºC and raise the pressure up to 0.5 MPa. As shown in Fig. 1, this operating condition can cover wide range of Σ. The value of Σ of 140 ºC water is approximately corresponding to liquid Nitrogen of 77 K and liquid Oxygen of 110 K.

Temperature of water was increased and controlled by using electric heater with accuracy of 0.1 ºC. The pressure of free stream was measured at upstream and downstream of test body with pressure transducer. The flow velocity and its distribution were measured with LDA (FlowLite 2D, Dantec Dynamics). The vertical distribution of streamwise velocity is shown in Fig. 3. The velocity distribution of vertical direction was measured without test body. The thickness of boundary layer was about few millimeters. Uniform flow velocity distribution was achieved around the center of the test section. NACA0009 hydrofoil with 30 mm chord length, 2.7 mm maximum thickness and 19.73 mm span width was used as a test body. M-Dreyer et al. investigated the influence of the gap width on both trajectory and intensity of the tip vortex cavitation with dimensionless gap width τ/h from 0 to 2 [7]. Their study showed a maximum influence at the dimensionless gap width 0.3. In the present study, for first stage of the experiment, gap width τ was set as constant value in 0.27 mm, dimensionless gap width 0.1.

Table 1 shows experimental condition, corresponding thermodynamic parameter and Reynolds number. For reference, in case of a real inducer in liquid propellant rocket engine in Japan, working fluid is liquid oxygen, Reynolds number $Re = UD / \nu$ (D is diameter of inducer, U is peripheral speed of inducer tip) is about 1.2×10^6 [8].

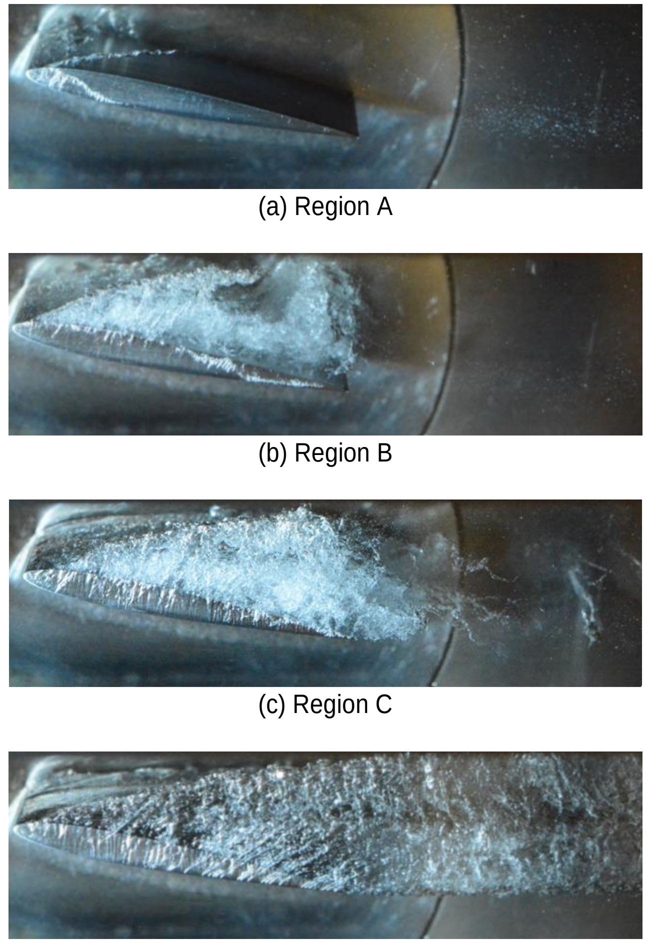
To measure temperature of cavity, thermistor probe (Nikkiso-Thermo Co., Ltd.) was inserted into the test section with stainless steel pipe of diameter 2 mm and thickness 0.5 mm. The configuration of test body and inserted thermistor probe is shown in Fig. 4. The angle of attack was 12 degree and temperature of cavity was measured at 14 mm downstream from hydrofoil leading edge by temperature probe T_c shown in Fig. 4. Additionally, temperature probe is inserted from backside wall in order to place the thermosensitive part inside the tip leakage cavity which is in upper part of tip clearance in frontside wall. The reference temperature was measured at 10 mm below and 20 mm ahead the center of flow channel by the probe T_∞. The thermosensible part of thermistor was placed inside a tip leakage cavitation which is upper part of tip clearance of the hydrofoil. To reduce the influence of temperature variation of free stream, the temperature of the cavity and free stream were measured simultaneously. All thermistor were calibrated before conducting experiment with quartz thermometer. Thermistor shows large change of electric resistance depending on temperature, so measurement of temperature with high accuracy is enabled. The resistance of thermistor was measured with digital multi meter, and the uncertainly of temperature measurement was less than 0.02 K. The influence of heat conduction from tunnel wall exists and steady-state heat conduction analysis was conducted. The estimated difference between temperature of thermistor and temperature of cavity was less than 4 %. Estimated time constant of the temperature probe was less than 5.42 s. The temperature of cavity was obtained by averaging 30 s of measurement results.

3. RESULTS AND DISCUSSION

3.1 Aspect of tip leakage cavitation

First, the cavity type on a hydrofoil with the leakage flow was observed. Higashi et al. classified the leakage vortex cavity in four regions from the configurations of the cavity [9]. In our experimental result, four kinds of tip leakage cavity were also observed, although the pattern was somewhat different from that in Higashi et al. In Fig. 5. the aspect of cavitation in NACA0009 with chord length C = 30 mm and tip clearance τ = 0.27 mm in the condition of flow temperature T_∞ = 30 °C, U_∞ = 10 m/s, AoA = 12 deg are shown. These photographs were taken without inserting temperature probe. In Region A, at higher cavitation number, tip vortex cavitation was observed intermittently near the leading edge at the tip. As the cavitation number decreases, in Region B, tip vortex cavitation, leakage vortex cavitation, and partial cavitation appear. In this region, small partial cavitation and leakage vortex cavitation oscillate with smaller amplitude and realtively high frequency. The oscillation of small partial cavity is well known through some experiments by several researchers. Arndt et al. conducted numerical and experimental investigation about sheet/cloud cavitation, and experiments were conducted at two different water tunnel with 2D NACA0015 hydrofoil [10]. Kawanami et al. experimentally investigated genaration mechanism of cloud cavitation on a hydrofoil by controlling cloud cavitation with an obstacle [11]. As the cavitation number decreases more, in Region C, the cavity cyclically changes from small partial cavitation and tip leakage cavitation to super cavitation with low frequency oscllation. Some experimental studies about the kind of oscillating cavitation, specifically in case of sheet/cloud cavity, are conducted. Wade et al. brought to attention about oscillating cavitation [12]. Sato et al. experimentally investigated the characteriscs of oscillating cavitation on a flat plate hydrofoil in a water tunnel [13]. It is thought that this tendency agrees with the case of the tip leakage cavity. Cavitation disappears and appears unsteadily during Region B and Region C, so this area is set of transition region. After that, in Region D, as the cavitation number decreases further, the cavity becomes to a leakage supercavitation.

Fig. 6 shows comparison of the occurence map of cavitation pattern in each angle of attack and cavitation number between low temperature water 30 °C and high temperature water 90 °C. For both figures, experimental condition is U_∞ = 10 m/s. As shown in Fig. 6, there is no significant difference of configurations of the cavity as a whole between 30 °C and 90 °C. In our previous experimental studies about sheet cavity and sheet/cloud cavity of separation type in water of 30 °C and 80 °C [2], there was also no significant change of cavitation pattern between 30 °C and 80 °C. So, it is shown that cavitation which is vortex type shows the similar tendency of which is separation type up to 90 °C. However, incipient cavitation number at 90 °C is higher than 30 °C in case of that angle of attack is 12 deg. It is thought that this is because scale effect in high Reynolds number condition is easy to appear at high temperature, and



(a) Region A

(b) Region B

(c) Region C

(d) Region D

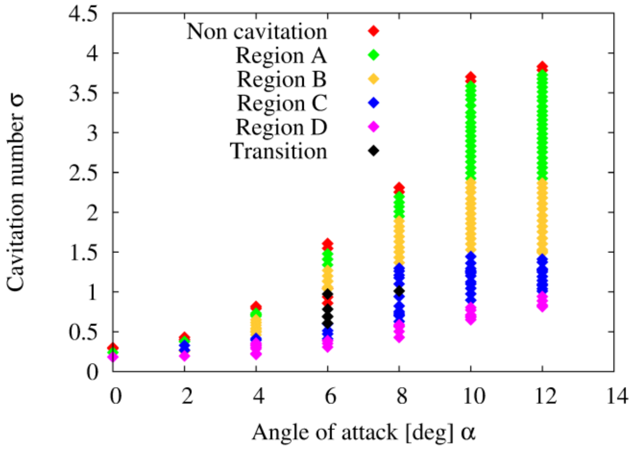
Figure 5. Appearance of cavity in water (T_∞ = 30 °C, U_∞ = 10 m/s, AoA = 12 deg).

tip vortex is strong with high angle of attack [14], so tip vortex cavitation remains undefeated in this case.

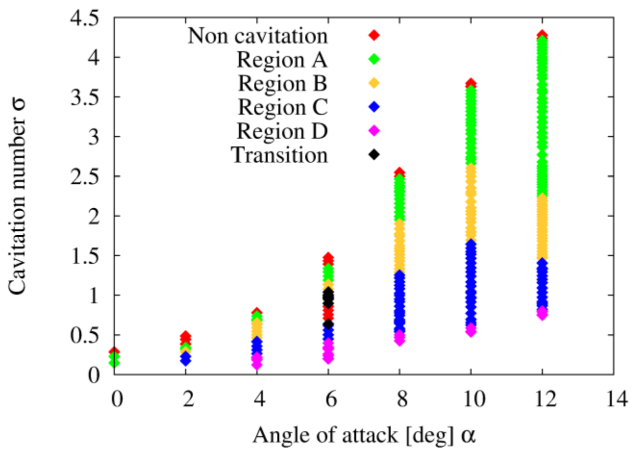
3.2 Measurement of temperature

In this study, the temperature of free stream was varied from room temperature to 90 °C and temperature inside a tip leakage cavity is measured by temperature probe. The aspect of a flow field with the temperature probe is shown in Fig. 7. This figure is snapshot of supercavitation at σ = 0.76, U_∞ = 10 m/s and angle of attack is 12 deg. In this figure, it is confirmed that cavitation is not caused by thermistor probe T_∞.

Fig. 8 shows the result of influence of cavtitation number on temperature depression in tip leakage cavity on the condition of T_∞ = 90 °C, U_∞ = 10 m/s and AoA = 12 deg. As cavitation number decreases, the temperature depression in tip leakage cavity becomes large. This tendency is in agreement with the experimental result of temperature depression in separation type cavity with hot water [2], and the experimental and numerical analysis of cavitating orifice flow with liquid nitrogen [15]. In the region of 0.9 < σ < 1.4, Region C, cavity length cyclically changes from small partial cavitation and tip leakage cavitation to super cavitation, so the thermistor



(a) T_∞ = 30 °C



(b) T_∞ = 90 °C

Figure 6. Mapping of cavitation pattern (U_∞ = 10 m/s)

Figure 7. The aspect of the temperature probe. The red circles in this figure denote the position of thermistor probe.

probe was covered with both cavity and water alternately. In the region of σ > 1.4, Region B, shedding of cavity was observed. So the thermistor was also coverd with both cavity and water cyclically. Therefore, the measured teperature was some sort of time averaged temperature. In Region D, maximum temperature depression reaches over 0.4 °C in tip leakage cavitation in super cavitation condition, in which the accuracy of temperature measurement is relatively higher than that in Region B and C.

Fig. 9 shows the result of influence of free stream temperature on temperature depression in tip leakage cavity

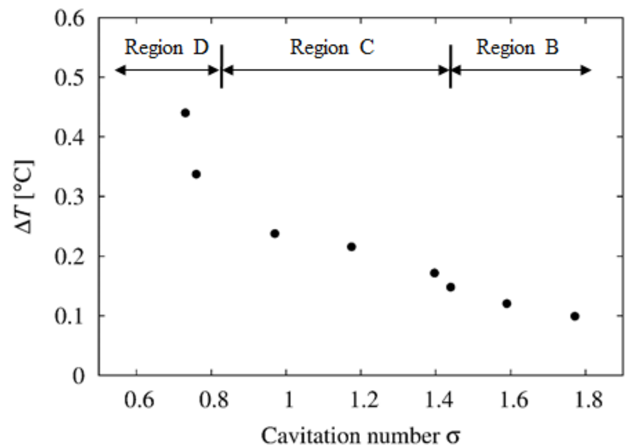


Figure 8. Influence of cavitation number on the temperature depression inside tip leakage cavity (T_∞ = 90 °C, U_∞ = 10 m/s, AoA = 12 deg)

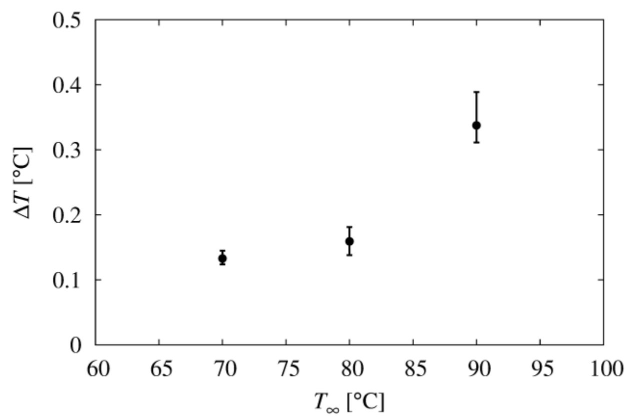


Figure 9. Influence of free stream temperature on the temperature depression inside tip leakage cavity (U_∞ = 10 m/s, AoA = 12 deg, σ = 0.76)

on the condition of supercavitation. Experimental condition is U_∞ = 10 m/s, AoA = 12 deg and σ = 0.76. The value of thermodynamic parameter is from 387.4 to 1610.6 m/s$^{3/2}$ for free stream temperature from 70 °C to 90 °C, the cavities are in Region D in all condition, which is super cavitation. From this result, it is shown that temperature depression become large according to increase of free stream temperature inside a tip leakage cavity in super cavitation condition.

4. CONCLUSION

Thermodynamic effect on tip leakage cavitation on a hydrofoil with tip clearance in high temperature water was studied with high temperature and high pressure water cavitation tunnel.

- Cavitation pattern of the tip leakage cavitation in NACA0009 hydrofoil was classified into four types.

- It was shown that there was no significant change in occurrence region of the each type of tip leakage cavitation in a temperature range from 30 °C to 90 °C. This tendency is similar to cavitation which is separation type on a hydrofoil without tip clearance.
- Temperature depression in tip leakage cavity was measured with thermistor probe. Observed maximum temperature depression was about 0.4 °C on the condition of super cavitation in water of 90 °C.

Further study will be conducted for following topics.

- Experiments with tip clearance variation in order to investigate the relationship of gap width and thermodynamic effect.
- Estimation of vorticity by numerical simulation in order to consider influence of vorticity on thermodynamic effect.

NOMENCLATURE

c_{pl} heat capacity of liquid [J]
p_∞ free stream pressure [MPa]
p_v pressure of vapor [MPa]
L latent heat of vaporization [J/kg]
T_∞ temperature of free stream [°C]
T_c temperature in cavity [°C]
ΔT temperature difference between free stream and cavity [°C]
U_∞ free stream velocity [m/s]
α_l thermal diffusivity of liquid [m²/s]
σ cavitation number = $(p_\infty - p_v) / (\rho U_\infty^2/2)$ [dimensionless]
ρ_l density of liquid [kg/m³]
ρ_v vapor density [kg/m³]
Σ thermodynamic parameter [m/s$^{3/2}$]
τ gap width [mm]
h foil maximum thickness [mm]
Re Reynolds number $U_\infty C / \nu$ [dimensionless]
ν kinematic viscosity [m²/s]
C chord length [mm]

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