Proceedings of the ASME 2014 4th Joint US-European Fluids Engineering Division Summer Meeting and 11th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM2014
August 3-7, 2014, Chicago, Illinois, USA

FEDSM2014-21433

Thermodynamic Effect on Cavitation in High Temperature Water

Yuki Yamaguchi
Graduate School of Engineering
Tohoku University
Sendai, Miyagi, Japan

Yuka Iga
Instituted of Fluid Science
Tohoku University
Sendai, Miyagi, Japan

ABSTRACT

Thermodynamic effect on cavitation appears in cryogenic fluids, refrigerant and high temperature water. The thermodynamic effect is considered to suppress the development of cavitation and improve the performance of hydraulic machinery. However, the actual appearance degree of thermodynamic effect depends on not only thermal property of each fluid but also each hydraulic machinery and its operating condition. So, the clarification of the influence of the flow field with unsteady cavitation on the degree of thermodynamic effect is necessary. In order to investigate thermodynamic effect, many experiments had been conducted with using cryogenic fluids or refrigerant as working fluids. However, there are some difficulties to visualize cryogenic fluids and the experimental results cannot be directly correlated to the condition without thermodynamic effect in same fluid.

In the present study, in order to conduct cavitation experiments with and without thermodynamic effect in same fluid, high temperature and high pressure cavitation tunnel had been constructed. The working fluid of this tunnel is water and the free-stream temperature can be varied from room temperature to 140 ℃. In the present study, NACA 0015 hydrofoil had been chosen as a cavitator.

The extent of thermodynamic effect was estimated through the measurement of temperature in the cavity. The temperature was measured by a thermistor probe which has high accuracy. When the thermodynamic effect appears, temperature depression in the cavity is observed. The maximum temperature depression of cavity about 0.3 K had been measured in water of 80 ℃.

INTRODUCTION

Cavitation occurs when the pressure of fluid is decreased below the vapor pressure. The occurrence of cavitation deteriorates the performance of hydraulic machinery. The strong pressure waves generated by the collapse of cavitation bubbles damage components of hydraulic machinery. So, influence of cavitation cannot be neglected in the design of hydraulic machinery and to understand the behavior of cavitation is necessary. A number of cavitation studies have been conducted for cavitation in water of room temperature. However, if the working fluid is replaced to cryogenic fluid, the behavior of cavitation is different from that of cavitation in room temperature water. The vaporization of liquids needs latent heat to be supplied from liquids around the cavity, and temperature of liquid around cavity is decreased. As a result, vapor pressure is decreased and the growth of cavity is suppressed. Thus, the performance of hydraulic machinery is improved. This suppression of cavity growth and improvement of performance of hydraulic machinery are called thermodynamic effect. Thermodynamics effect on cavitation in water of room temperature is negligibly small, however, cavitation in the cryogenic fluids, high temperature water and fluids whose temperature is close to critical temperature it becomes significant and cannot be neglected. The extent of thermodynamic effect is known to increase with increasing temperature of working fluid, however, Cervone et al. [1] report diverse behavior of cavitation in water of 70 ℃, the occurrence of cloud cavitation and supercavitation shifts toward higher cavitation number compared to water of 25 ℃. The extent of thermodynamic effect and its appearance temperature are still unclear, it depend on not only thermal property of the fluid but also depend on flow conditions of each hydraulic machinery. So, in order to enable appropriate design of hydraulic machinery, which can effectively use thermodynamic effect, the clarification of thermodynamic effect is necessary.

The thermodynamic parameter Σ proposed by Brennen [2] 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 considered to describe the cause of thermodynamic effect, however, the incidence of thermodynamic effect 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. investigate a cavitating inducer in R114 and estimate the temperature depression in cavity by comparing the experimental results of cavitating inducer in room temperature water [3]. Niiyama et al. visualize cavitating hydrofoil in liquid Nitrogen and measure temperature depression in the cavity [4]. Many experimental research of thermodynamic effect were conducted with 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 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 constructed in the present study. The working fluids of this tunnel is water and the free-stream temperature can be varied from room temperature to 140 ℃. In the present study, NACA 0015 hydrofoil had been chosen as a cavitator, and temperature of cavity was measured by using thermistor probe.

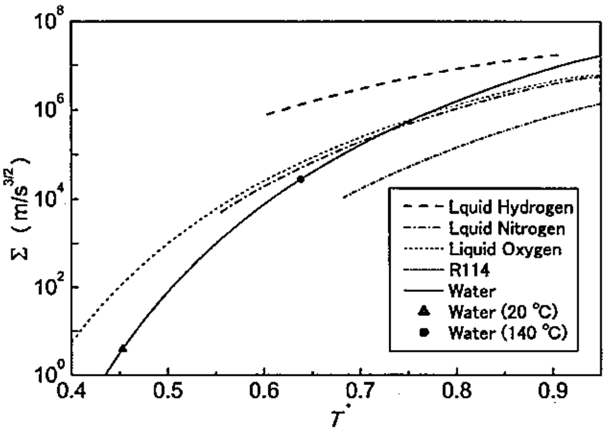

Figure 1. Thermodynamic parameter Σ of some cryogenic fluids, R114 and water.

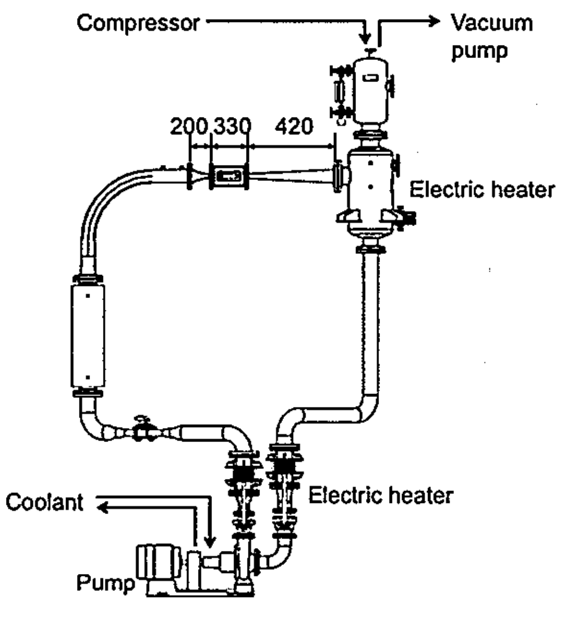

Figure 2. Overview of high temperature and high pressure water cavitation tunnel.

THERMODYNAMIC EFFECT

In this study, water is used as working fluid and by varying temperature of water the thermodynamic effect on cavitation is investigated. Figure 1 shows thermodynamic parameter Σ of some cryogenic fluids, refrigerant and water. T^* is temperature normalized by critical temperature of each fluid. Thermodynamic parameter Σ of room temperature water 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 ℃ 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 ℃ had been constructed.

To estimate the extent of thermodynamic effect temperature in the cavity was measured. The cavitation number without thermodynamic effect is described as,

$$\sigma = \frac{p_\infty - p_v(T_\infty)}{\frac{1}{2}\rho_l U_\infty^{\ 2}} \tag{2}$$

where p_∞ is pressure of free stream, p_v is pressure of vapor and U_∞ is velocity of free stream. When thermodynamic effect appears, temperature of the cavity, T_c, is different from temperature of free stream, T_∞, and cavitation number considering thermodynamic effect is described as,

$$\sigma_c = \frac{p_\infty - p_v(T_c)}{\frac{1}{2}\rho_l U_\infty^{\ 2}} \tag{3}$$

where T_c is temperature in cavity. These two cavitation numbers can be correlated as,

$$\Delta\sigma = \sigma_c - \sigma = \frac{1}{\frac{1}{2}\rho_l U_\infty^{\ 2}} \frac{dp_v}{dT} \Delta T \tag{4}$$

Thus, temperature depression, ΔT, can be used to describe the extent of thermodynamic effect on cavitation [3]. And, Kato et al. proposed Z-factor theory to describe pressure drop caused by thermodynamic effect [5]. By assuming boundary layer of cavity surface is laminar or, when boundary layer is turbulent, thermal diffusivity is constant, they derived following equation to describe the difference of cavitation number,

$$\Delta\sigma = C_z \frac{L}{k_l}\frac{dp_v}{dT}\sqrt{\frac{\rho_v \alpha_l}{\rho_l U_\infty{}^3}} \quad (5)$$

where C_z is constant, k_l is heat conductivity of liquid and α_l is thermal diffusivity of liquid. From eq. (4) and eq. (5), ΔT is described as follows,

$$\Delta T = \frac{C_z L}{2k_l}\sqrt{\rho_v \rho_l \alpha_l U_\infty} \quad (6)$$

Thus, from analysis of Z-factor theory, the temperature depression caused by thermodynamic effect is considered to be proportional to $U_\infty{}^{1/2}$.

EXPERIMENTAL SET UP

New cavitation tunnel was constructed to conduct cavitation experiment of high temperature and high pressure water. The overview of this tunnel is shown in Figure 2. This tunnel is made of stainless steel. The geometry of flow channel is 30 mm × 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 ℃ and raise the pressure up to 0.5 MPa. As shown in Figure 1, this operating condition can cover wide range of Σ. The value of Σ of 140 ℃ 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 ℃. 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 Figure 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.

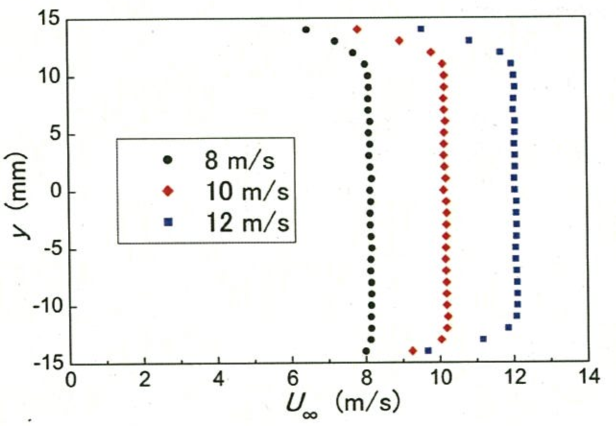

Figure 3. Vertical distribution of streamwise velocity.

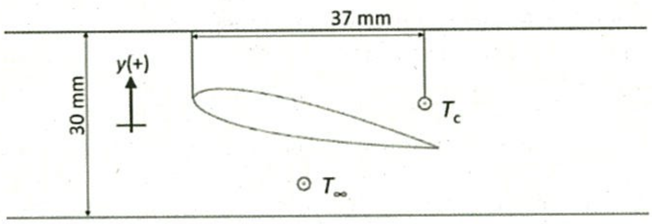

Figure 4. Configuration of temperature probe and NACA 0015 hydrofoil (chord length 40 mm, angle of attack 12 deg).

NACA 0015 hydrofoil with 40 mm chord length and 20 mm span width was used as a test body. 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 Figure 4. The angle of attack was 12 degree and temperature was measured at 37 mm downstream from hydrofoil leading edge by temperature probe T_c shown in Figure 4. The reference temperature was measured at 10 mm below the center of flow channel by the probe T_∞.

The thermosensible part of thermistor was placed mid span of flow channel. To reduce the influence of temperature variation of free stream, the temperature of the cavity and free stream were measured simultaneously. All thermistors were calibrated before conducting experiment with quartz thermo meter. Thermistor shows large change of electric resistance depending on temperature, so measurement of temperature with high accuracy was enabled. The resistance of thermistor was measured with digital multi meter, and the uncertainty 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 10 %. Estimated time constant of the temperature probe was less than 5.42 s. The temperature of cavity was obtained by averaging 20 s of measurement results.

RESULT AND DISCUSSION

In this study the temperature of free stream was varied from room temperature to 80 ℃. Table 1 shows experimental conditions and corresponding thermodynamic parameter. Figure 5 and Figure 6 show the aspects of cavitation in water of 20 ℃ and 80 ℃ respectively. For both figures, U_∞ = 8 m/s and angle of attack is 12 deg. In both figures, (a) is snapshot of supercavitation at σ = 2.0 and (b) is unsteady cavitation with periodical cloud shedding at σ = 1.6. These snapshots are chosen at random, so the length of cavitation cannot compared. On the condition of supercavitation temperature probe is fully immersed into cavity. And on the condition of unsteady cavitation, it is confirmed that cavitation is not caused by temperature probe. The visualization results of cavitation in liquid Nitrogen show

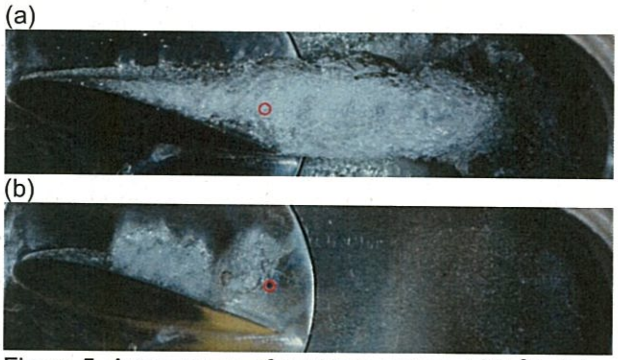

Figure 5. Appearance of cavity in water of 80 ℃. (a) σ = 1.6, (b) σ = 2.0. The red circles in these figures denote the position of thermistor probe to measure T_c.

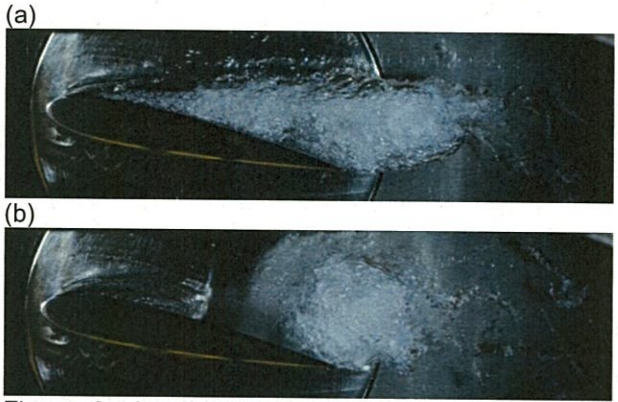

Figure 6. Appearance of cavity in water of room temperature (20 ℃). (a) σ = 1.6, (b) σ = 2.0. These photographs were taken without inserting temperature probe.

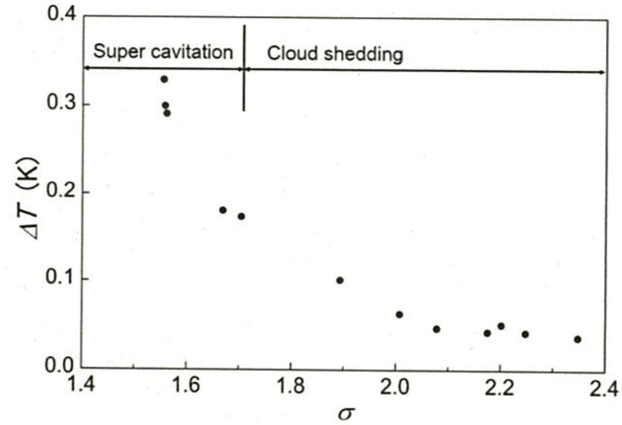

Figure 7. Relationship between temperature depression and cavitation number. (U_∞ = 8 m/s, T_∞ = 80 ℃, AoA = 12 deg)

Table 1. Experimental conditions and corresponding thermodynamic parameter.

AoA (deg)	12				
σ	1.6				
U_∞ (m/s)	8			10	12
T_∞ (℃)	40	60	80	80	80
Σ (m/s$^{3/2}$)	30.3	176.0	809.8	809.8	809.8

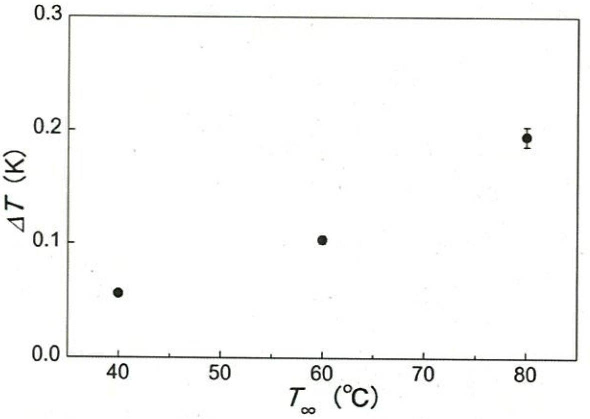

Figure 8. Relationship between temperature depression and temperature of free stream. (U_∞ = 8 m/s, σ = 1.6, AoA = 12 deg)

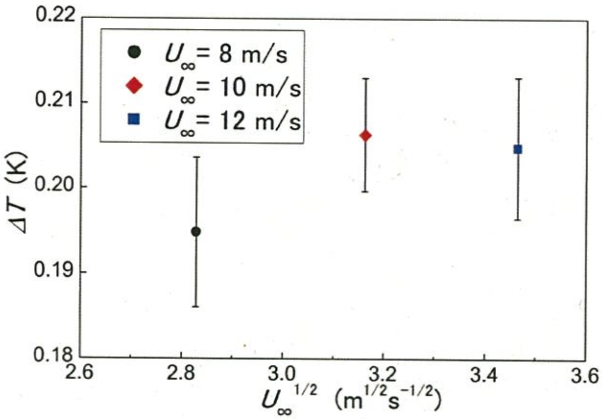

Figure 9. Relationship between temperature depression and velocity of free stream. (T_∞ = 80 ℃, σ = 1.6, AoA = 12 deg)

that cavity consist of a lot of tiny bubbles [4], one of the reason of the tiny bubbles is commonly considered to be thermodynamic effect. However, such cavity had not been observed for cavitation in water of temperature up to 80 ℃. And also, no significant difference of appearance was observed between these conditions.

Figure 7 shows the relationship between measured temperature depression and cavitation number on the condition of $U_\infty = 8$ m/s, $T_\infty = 80$ ℃ and AoA = 12 deg. The temperature of cavity, T_c, was decreased when the temperature probe is immersed into cavity. As cavitation number decreases, the temperature depression in cavity becomes large. Supercavitation had been observed at the region of cavitation number $\sigma < 1.7$ and periodical cloud shedding was observed at the region of $\sigma > 1.7$. From FFT analysis of upstream pressure fluctuation, peak frequency of 24 Hz relating to periodical cloud shedding was obtained at $\sigma = 2.0$. Although the cavitation pattern transits to supercavitation around $\sigma = 1.7$, the temperature depression increases continuously with decreasing cavitation number. On the conditions of periodical cloud shedding occurs ($\sigma > 1.7$) the temperature probe was immersed both water and cavity alternately, so the measured temperature was some sort of time averaged temperature. However, the heat transfer coefficient around the probe was changing periodically, the evaluation of measured value on this condition needs more careful consideration.

Figure 8 shows relationship between measured temperature depression and temperature of free stream at the conditions of supercavitation ($\sigma = 1.6$). As the temperature of free stream is increased, measured temperature depression become large. The value of thermodynamic parameter is from 30.3 to 809.8 m/s$^{3/2}$ for water of temperature from 40 ℃ to 80 ℃. The gradual increase of temperature depression was observed with increasing thermodynamic parameter.

Figure 9 shows the relationship between temperature depression and velocity of free stream. The horizontal axis of Figure 9 is $U_\infty^{1/2}$, so if ΔT is proportional to $U_\infty^{1/2}$ the plots of this graph become linear. From Z-factor theory [5], the degree of temperature depression is proportional to $U_\infty^{1/2}$ as described in Eq. (5). As shown in Figure 9, ΔT is not proportional to $U_\infty^{1/2}$. Z-factor theory assumes boundary layer of cavity surface is laminar or, when boundary layer is turbulent, thermal diffusivity is constant. So, it can be conceivable that an influence may come out, in which thermal diffusivity is not constant on the boundary layer of cavity surface.

CONCLUSION

Thermodynamic effect on cavitation in high temperature water was studied with newly constructed high temperature and high pressure water cavitation tunnel. The results are summarized as follows.

- Temperature depression in cavity was measured with thermistor probe. Maximum temperature depression of about 0.3 K was observed on the condition of supercavitation around NACA0015 in water of 80 ℃.
- Dependence of extent of temperature depression on free stream temperature was confirmed by the present measurement method.
- Non-uniformity of thermal diffusivity on boundary layer of cavity surface is conceived.

Further study will be conducted for following topics.

- Evaluation method of temperature depression caused by unsteady cavitation and relationship between temperature depression and cavity length.
- The extent of temperature depression for each free stream temperature up to 140 ℃.
- The effect of free stream velocity and other flow conditions such as turbulent intensity on the temperature depression.

NOMENCLATURE

c_{pl} heat capacity of liquid
k_l heat conductivity of liquid
p_∞ pressure of free stream
p_v pressure of vapor
C_z constant
L latent heat of vaporization
T_∞ temperature of free stream
T_c temperature in cavity
T^* temperature normalized by critical temperature
ΔT temperature difference between free stream and cavity
U_∞ velocity of free stream
α_l thermal diffusivity of liquid
σ cavitation number
ρ_l density of liquid
ρ_v density of vapor
Σ thermodynamic parameter

ACKNOWLEDGMENTS

This study was financially supported by JSPS KAKENHI Grants-in-Aid for Young Scientists. Authors would like to thank Prof. H. Kato for his advice about experimental facility.

REFERENCES

[1] A. Cervone, C. Bramanti, E. Rapposelli and L. d'Agostino, 2006, "Thermal Cavitation Experiments on a NACA 0015 Hydrofoil" J. Fluids Eng., Vol. 128, pp. 326-331
[2] C. E. Brennen, "Cavitation and Bubble Dynamics", Oxford University Press.
[3] J. P. Franc, C. Rebattet and A. Coulon, 2004, "An Experimental Investigation of Thermal Effects in a Cavitating Inducer", J. Fluids Eng., Vol. 126, pp. 716-723
[4] K. Niiyama, Y. Yoshida, S. Hasegawa, M. Watanabe and M. Oike, "Experimental Investigation of Thermodynamic Effect on Cavitation in Liquid Nitrogen", Proceedings of the Eighth International Symposium on Cavitation (CAV2012), pp. 153-157
[5] H. Kato, 1984, "Thermodynamic Effect on Incipient and Developed Sheet Cavitation", International Symposium on Cavitation Inception, FED-Vol. 16, pp. 127-136