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Interaction between Thermodynamic Suppression Effect and Reynolds Number Promotion Effect on Cavitation in Hot Water

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Abstract In this study, in order to clarify a interaction between thermodynamic effect, which suppresses cavitation, and scale effect, which promotes cavitation, tunnel experiment was done with NACA16012 single hydrofoil in hot water. Appearance of the effects was estimated by occurrence condition of cavitation for angle of attack vs cavitation number. And the cause of thermodynamic effect is estimated by measuring the temperature depression inside the cavity. Mainstream temperature was 30 ℃ and 70 ℃. By increasing mainstream temperature under constant Reynolds number condition, scale effect was took away to some extent and thermodynamic effect was picked out. From the result, occurrence resin of cavitation was suppressed in 70 ℃ hot water, where it is empirically known that thermodynamic effect does not appear in such a low temperature. The result indicates that thermodynamic effect and scale effect, which are conflicting effects, cancelled each other in water at 70 ℃. Additionally, it was shown that occurrence of cavitation was drastically suppressed in a condition under specific range of angle of attack.

Keywords: Thermodynamic effect, Scale effect, Hot water, NACA16012, Thermistor

Introduction

Generally, volume of cavitation is same when a cavitation number σ is same in the flow field around same body. An effect which breaks the similarity raw is known as scale effect. The scale effect is caused by the influence of nuclei. When the Reynolds number Re in mainstream is higher, the cavity inception moves higher cavitation number condition [1,2]. Also, cavity volume is bigger when Re is higher in spite of same σ condition [3].

On the other hand, in many fluids except for room temperature water, when mainstream temperature T_∞ is higher, the cavity volume is smaller in spite of same σ condition. The effect is known as thermodynamic effect [4-8]. The mechanism of the suppression of cavity volume is that when a cavity occurs, the local temperature decreases around the cavity due to the latent heat of evaporation of the cavity. The local saturated vapor pressure decreases due to the temperature depression, and evaporation is then suppressed. The factor of the thermodynamic effect is expressed by the thermosphysical properties of each fluid in each condition, the effect is known to become obvious in cryogenic fluids such as liquid hydrogen and liquefied natural gas as well as in hot water and refrigerant. The thermodynamic effect is scale effect in a broad sense because cavity volume is different in same σ, but it is distinguished from scale effect which appears without thermal influence. Hence, the thermodynamic effect is also distinguished from scale effect in the present study.

When T_∞ increases, Re increases due to decrease of the viscosity. At that time, conflicting two effects is considered to interact with cavitation, which are suppression effect by the thermodynamic effect and promotion effect by the scale effect. Generally, nuclei are small in number in cryogenic fluid, then thermodynamic effect is obvious. On the other hand, in a tap water, nuclei are comparatively in large number and the scale effect cannot be neglected. Cervone et al. reported the opposite thermodynamic effect in a single hydrofoil experiment using hot water [9], in which the cavity volume increased according to increase T_∞ in unsteady cavitation condition. We assume it is a result from that the scale effect exceeded the thermodynamic effect in the experiment.

In the present study, experiment of NACA16012 single hydrofoil in hot water tunnel is done in order to reveal the relationship between thermodynamic effect and scale effect in hot water. Two kinds of comparison are done about occurrence range of cavitation with T_∞ change, one is in constant mainstream velocity U_∞ condition which corresponds an experiment of conventional thermodynamic effect and the other is in constant Re condition where scale effect is removed in some degree. T_∞ is increased from 30 ℃ to 70 ℃. In the temperature range, it is empirically known thus far that the thermodynamic effect is not obvious or reversely appears. Additionally, temperature depression inside the cavity which is a factor of the thermodynamic effect.

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Experimental Condition

The present experiment is done in high-temperature water cavitation tunnel in Institute of Fluid Science, Tohoku University [10]. The mainstream temperature T_∞ is increased from 30 ℃ to 70 ℃ in two conditions of constant mainstream velocity U_∞ and constant Reynolds number Re. Although in the temperature range, it is empirically known that the thermodynamic effect is not obvious, it is widest range in constant Re condition in the present tunnel. Mainstream velocity is U_∞ = 6.9 m/s and U_∞ = 13.4 m/s. The test body is NACA16012 single hydrofoil of chord length 30 mm. The angle of attack is incremented by 1 degree from 0 to 9 degree. Definitions of Cavitation number s, Reynolds number Re, thermodynamic parameter Σ [5] and non-dimensional thermodynamic parameter Σ^* [11] are follows.

Cavitation Number : $$\sigma = \frac{p_\infty - p_v}{1/2\rho_\infty U_\infty^{\ 2}} \tag{1}$$

Reynolds Number : $$\mathrm{Re} = \frac{U_\infty C}{v_\infty} \tag{2}$$

Thermodynamic Parameter : $$\Sigma = \frac{\rho_v^{\ 2} L^2}{\rho_l^{\ 2} C_{pl} T_\infty \sqrt{a_l}} \tag{3}$$

Non-dimensional Thermodynamic Parameter : $$\Sigma^* = \frac{\rho_v^{\ 2} L^2}{\rho_l^{\ 2} C_{pl} T_\infty}\sqrt{\frac{C}{a_l U_\infty^3}} = \Sigma\sqrt{\frac{C}{U_\infty^3}} \tag{4}$$

In above equations, p_∞ [Pa], ρ_∞ [kg/m^3], v_∞ [Pa s] and p_v [Pa] are static pressure, density, viscosity and saturated vapor pressure in mainstream, respectively. ρ_v [kg/m^3] is vapor density at mainstream pressure and temperature. L [J/kg] is latent heat. C_{pl} [J/(kg・K)] and α_l [m^2/s] are isobaric specific heat and thermal diffusivity of water. C [m] is chord length of hydrofoil. The bigger Σ become, the larger thermodynamic effect become, then cavity volume suppressed. Σ^* takes into account time interval for heat transfer. Then, the lower mainstream velocity is, the bigger thermodynamic effect becomes.

The fluid is degassed tap water, degree of oxygen saturation is 30％(±3.0％以内） at 30 ℃. In addition, the oxygen saturation cannot be measured after rising T_∞. And number of nuclei cannot be controlled. Therefore, the scale effect cannot be completely removed away although in constant Re condition.

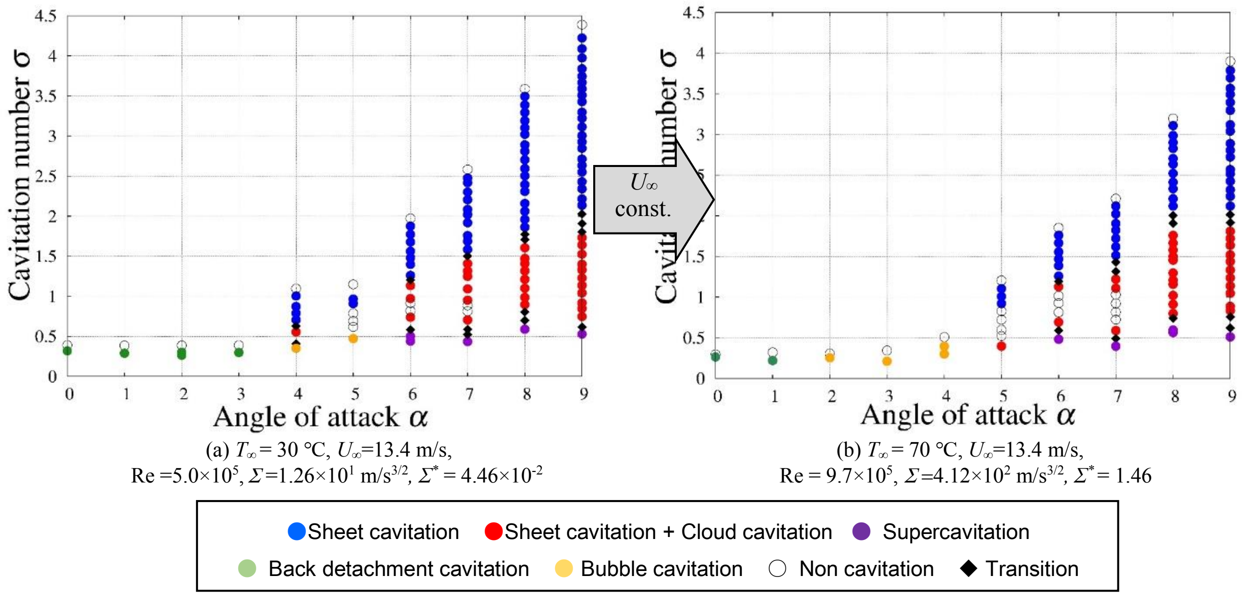
Results

A. Influence of Mainstream Temperature under Constant Velocity Condition

Occurrence range of cavitation and the pattern is determined from visualization of the aspect and frequency analysis of pressure fluctuation downstream of the test section. The resulting cavitation pattern map of NACA16012 hydrofoil is shown in Fig. 1 (a) about angle of attack α versus cavitation number σ in a condition of mainstream temperature T_∞ = 30 ℃ and mainstream velocity U_∞ = 13.4 m/s. In the flow condition, five kinds of cavitation patterns are observed, which are attached sheet cavitation, sheet-cloud cavitation, supercavitation, bubble cavitation and back detachment cavitation. In addition, a case in which cavitation pattern changes from one to another and the pattern is hard to distinguish is expressed by transition in the map.

In Fig 1 (a) where T_∞ = 30 ℃ and U_∞ = 13.4 m/s, according to increase of α, occurrence range extends to higher σ condition. At higher α condition from 6 deg. to 9 deg., attached sheet cavitation, sheet-cloud cavitation and supercavitation occurs in order according to decrease of σ. At α = 4 and 5 deg., bubble cavitation occurs in lower σ condition. At lower α condition from 0 deg. to 3 deg., back detachment cavitation occurs. The cavitation pattern map of NACA16012 was also made by Franc in room temperature water [12]. Although the cavitation pattern was no so far from the present result, but the occurrence condition of each pattern was different in some degree. It is because the tunnel scale and water quality were different from the present tunnel and the experiment was done with free surface condition.

Usually, thermodynamic effect is discussed by increasing T_∞ in a condition of constant U_∞. Then, the case where T_∞ is increased to 70 ℃ in the constant U_∞ condition at U_∞ = 13.4 m/s is shown in Fig 1 (b) and compared. In the condition, although the occurrence range slightly decreases at α = 4 deg. and over 7 deg., but there is not so large suppression occurrence range in Fig 1 (b) compared with Fig 1 (a). Additionally, although back detachment cavitation changes to bubble cavitation at α =2 deg. and 3 deg., but there is not so large difference in the cavity patterns except for that. The result agrees with common knowledge in which thermodynamic suppression effect does not appear in a hot water under T_∞ = 70 °C.



(a) T_∞ = 30 °C, U_∞=13.4 m/s, Re =5.0×10^5, Σ=1.26×10^1 m/s$^{3/2}$, Σ^* = 4.46×10^{-2}

(b) T_∞ = 70 °C, U_∞=13.4 m/s, Re = 9.7×10^5, Σ=4.12×10^2 m/s$^{3/2}$, Σ^* = 1.46

Fig. 1 Influence of increase of mainstream temperature on cavitation pattern map in a condition of constant mainstream velocity U_∞.

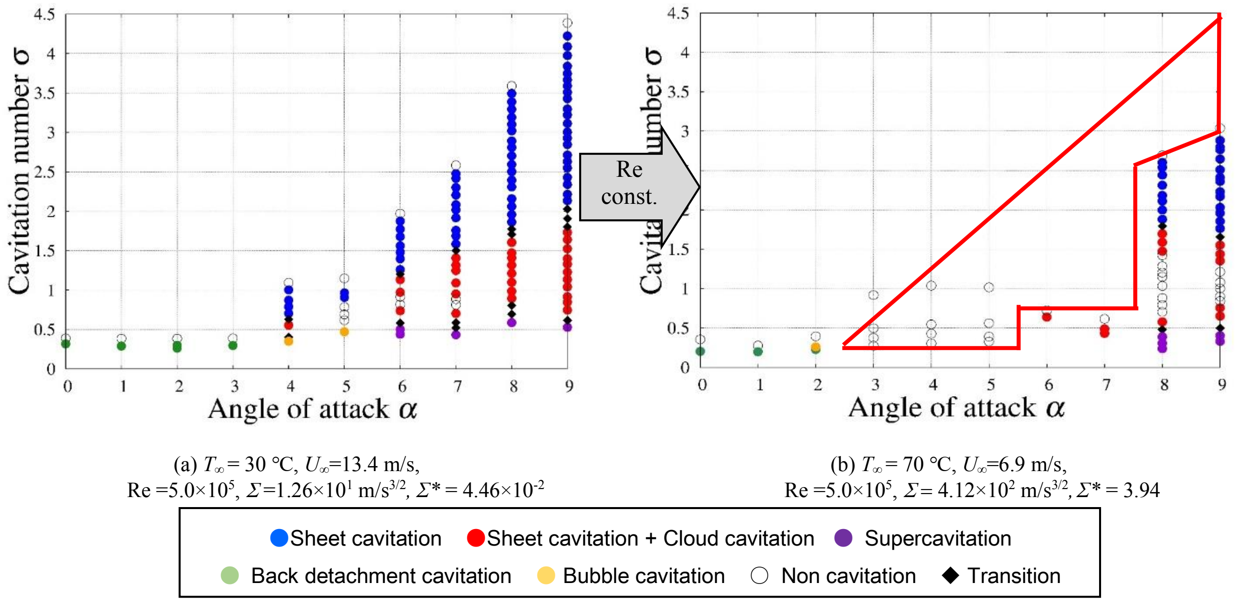
B. Influence of Mainstream Temperature under Constant Reynolds Number Condition

In the comparison in Fig 1, Reynolds number Re also increases at T_∞ = 70 °C in Fig 1 (b). Then, scale effect which is promotion effect of cavitation is considered to also affect on the cavitation with thermodynamic suppression effect in Fig 1 (b). Therefore, in order to reduce the scale effect, T_∞ is increased from 30 °C to 70 °C under constant Re condition at Re =5.0×10^5 by decreasing of U_∞. The comparison of cavitation pattern map under constant Re condition is shown in Fig 2, where Fig 2 (a) is same figure in Fig 1 (a).

In the condition at T_∞ = 70 °C in Fig 2 (b), occurrence range of cavitation is drastically suppressed as indicated by the region enclosed by the red line. The result indicates that thermodynamic effect is hiding in 70 °C water which is relatively low temperature and it appears when scale effect is reduced. In addition, the result supports our assumption of the reason of opposite thermodynamic effect in the hot water experiment by Cervone [9], in which the scale effect exceeded the thermodynamic effect due to the tunnel condition.

The extension of occurrence range of cavitation from T_∞ = 70 °C, U_∞=6.9 m/s in Fig 2 (b) to T_∞ = 70°C, U_∞ = 13.4 m/s in Fig 1 (b) corresponds to the amount of promotion by scale effect. At the same time, it is also explained by decrease of non-dimensional thermodynamic parameter Σ^* in which time interval for heat transfer is reduced by increasing the mainstream velocity. But, the value of decreasing of Σ^* from Fig 2 (b) to Fig 1 (b) is 3.94 to 1.46, it is sufficiently smaller than that from Fig 2 (b) to Fig 2 (a) which is 3.94 to 4.46×10$^{-2.}$ Then, the contribution of reduction of thermal suppression effect is considered to be small in the extension of occurrence rage from Fig 2 (b) to Fig 1 (b). It is considered to be caused mainly by increase of scale effect.

The red line in Fig 2 (b) shows that the occurrence range of cavitation is drastically suppressed at the condition of angle of attacked between α = 4 deg. to 7 deg. It is important evidence that the degree of appearance of thermodynamic effect changes according to the change of local situation around a body although the mainstream condition is same. Franc et al investigated the relationship between the condition of boundary layer of suction side of a hydrofoil and cavitation pattern in same NACA16012 hydrofoil [12]. Although the Franc's tunnel condition was different from that in the present experiment as mentioned before, it was reported that the boundary layer changes from attacked laminar boundary layer with separation in around trailing edge, attached turbulent boundary layer with separation in around trailing edge to turbulent boundary layer separated from leading edge according to increase of angle of attack of the hydrofoil, and back detachment cavitation occurred in a condition of laminar boundary layer. Then, we are considering that thermodynamic effect is easy to appear in a boundary layer condition of attached turbulent boundary layer and now investigating. If the relationship between boundary layer condition and appearance of thermodynamic suppression effect will be clarified, it will be helpful in a design and development in fluid machinery.



(a) $T_\infty = 30$ °C, U_∞=13.4 m/s, Re =5.0×10^5, Σ=1.26×10^1 m/s$^{3/2}$, Σ^* = 4.46×10^{-2}

(b) $T_\infty = 70$ °C, U_∞=6.9 m/s, Re =5.0×10^5, Σ= 4.12×10^2 m/s$^{3/2}$, Σ^* = 3.94

Fig. 2 Influence of increase of mainstream temperature on cavitation pattern map in a condition of constant Reynolds number.

C. Temperature inside a Cavity

Temperature depression inside a cavity is measured, which is a cause of thermodynamic effect and the evidence of latent thermodynamic effect. The temperature is measured by thermistor probe which is inserted from the side wall of the cavitation tunnel to inside the cavity directory [10]. The temperature depression ΔT is estimated using the temperature inside a cavity subtracted by mainstream temperature which is also measured by thermistor probe inserted from the side wall to the mainstream without cavity in the test section. The result of ΔT is shown in Fig 3, where temperature depression is measured in the three cases in which U_∞=13.4 m/s at $T_\infty = 30$ °C, U_∞=6.9 m/s and 13.4 m/s at $T_\infty = 70$ °C at angle of attack $\alpha = 9$ deg. in all cases. And the error bar expresses expanded uncertainty of the temperature probe, which includes calibration and the repeated measurement. Because the time constant of the temperature probe is large, unsteady temperature cannot be measured and the measured temperature in unsteady

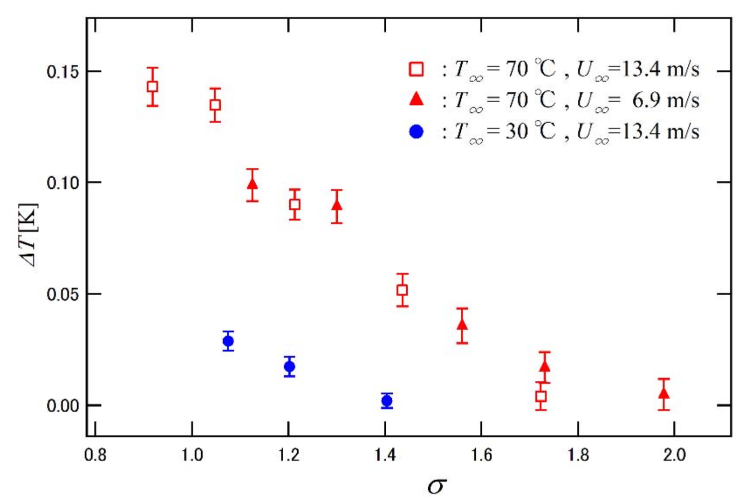


Fig.3 Temperature depression inside a cavity at angle of attack $\alpha = 9$ deg.

cavitation condition is time averaged value in some degree, but it is not strict time-average.

In Fig 3, the ΔT is larger in T_∞ = 70 °C than that in T_∞ = 30 °C, it means thermodynamic effect become larger in T_∞ = 70 °C than that in T_∞ = 30 °C. Additionally, in the two cases in T_∞ = 70 °C, the ΔT are almost same. Then, it is confirmed that thermodynamic effect is also hiding in the case of T_∞ = 70 °C and U_∞=13.4 in Fig 1 (b) in same degree in Fig 2 (b). Furthermore, the same ΔT in the two cases in T_∞ = 70 °C also confirms that the extension of the occurrence region of cavitation from Fig 2 (b) to Fig 1 (b) is not by the decrease of Σ^* but by the scale effect. Therefore, it is confirmed that two conflicting suppression and promotion effects, which are thermodynamic effect and scale effect, are superimposed and cancelled each other in the case in Fig 1 (b).

Conclusion

In the present study, through visualization of the aspect of cavitation and measurement of temperature inside the cavitation around NACA16012 single hydrofoil in hot water, relationship between thermodynamic effect and scale effect is investigated. The obtained results are summarized as follows;

1. By increasing mainstream temperature under a constant Reynolds number condition, because the scale effect is reduced in some degree, the thermodynamic suppression effect drastically appears. Then, it can be shown that thermodynamic effect is hiding also in 70 °C water in which it is empirically known that the thermodynamic effect is not obvious or reversely appears.

2. When mainstream temperature is increased under a constant mainstream velocity condition, the occurrence range of cavitation is not so suppressed. The reason is confirmed by temperature measurement inside the cavity that two conflicting suppression and promotion effects, which are thermodynamic effect and scale effect, are superimposed and cancelled each other in the case.

3. It is shown that occurrence of cavitation is drastically suppressed in a condition under specific range of angle of attack. It is important evidence that the degree of appearance of thermodynamic effect changes according to the change of local situation around a body although the mainstream condition is same.

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