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学位論文題目	Simplified Thermodynamic Model for Homogeneous Cavitation Analysis by Modification of Energy Equation (エネルギー方程式の修正によるキャビテーション均質解析のための簡略化熱モデル)
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論文内容要約

Chapter 1: General introduction

In this chapter, the background of present study is presented. Cavitation is the formation of vapor phase in the liquid phase when the local pressure reduces to around its saturation vapor pressure at constant temperature. Cavitation is major concern in the design of hydraulic devices such as turbo-machineries, propeller, and nozzle due to the performance degradation, noise and instability and erosion damage. Hence, it has been received widespread attention and intense investigate in many fields of engineering, ranging from aerospace to civil engineering, ship building to hydro turbine and pump industry.

It is known that thermodynamic effect is a good effect for turbomachine, which is significant when the liquid temperature close to the critical temperature such as in cryogenic liquid or hot water. When cavitation occurs, the latent heat for vaporization is supplied from the surrounding liquid, which decreases the local liquid temperature. That results in a drop of the saturated vapor pressure. The development bubble is therefore delayed and cavitation is suppressed. Hence, the performance of hydraulic machinery could be improved. Due to that behavior, the understanding of thermodynamic effect on cavitation is crucial for the design of the reliable and high performance of turbomachines.

The thermodynamic effect on cavitation has been experimentally investigated since 1960s. Problem gained that the existing experimental data is extremely scared owing to the limitation of measurement devices, high-cost, and difficulty in measure of temperature variation. Hence, most of existing studies were attended on the consequence of thermodynamic effect on cavitation rather than its mechanism. Although more efforts have been recently put into develop a CFD model for homogeneous model to predict the thermodynamic effect on cavitation, it is still unexplored and remains wide scope for improving numerical model, since almost none of present models can correctly predict the thermally controlled cavitation such as the temperature field.

Typically, the numerical simulation of cavitation with thermodynamic effect shows a tightly interaction of temperature and mass transfer rate. The temperature influences the rate of phase change through the saturated vapor pressure. At the same time, the mass transfer rate gains the temperature field through the thermodynamic model. Therefore, in order to predict the mechanism of cavitation with thermal effect, important thing is derivation of a thermal model for homogeneous model that could correctly predict the temperature field in cavitating flow.

Chapter 2: Numerical method for cavitating flow using homogeneous model

In this chapter, the physical locally homogeneous cavitation model was explained. The simplified thermodynamic model expressed for ρT as conservative value, which is derived from the mixture total energy equation, was proposed for homogeneous cavitation model. In this mode, the heat source S_h, which concerns latent heat of phase change L and mass transfer rate m, was explicitly appeared and could be adjusted to suit homogeneous model.

$$\frac{\partial \rho T}{\partial t}+\frac{\partial \rho T u_j}{\partial x_j}=\frac{1}{c_p}\frac{\partial}{\partial x_i}(\kappa\frac{\partial T}{\partial x_i})+\frac{S_h}{c_p},$$
$$S_h=-mL=-Lm^{+}-Lm^{-}=h_e+h_c. \tag{1}$$

The finite difference method with symmetric TVD-MacCormack scheme was explained. Present method was reasonable applied to simulate the cavitating flow behavior in both noncavitation to cavitation condition based on computational validation.

Chapter 3: Validation of present simplified thermodynamic model for homogeneous model

In this chapter, the applicable of present simplified thermodynamic model and present homogeneous model was validated for cryogenic problems such as liquid nitrogen (LN_2) cavitation and liquid hydrogen (LH_2) cavitation based on Hord's experimental data. The numerical result was quantified by compare with the time-averaged flow parameter in Hord's experiment and CFD data by existing thermal model.

Typically, a cavitation bubble shows the process of collapse and rebound. Additionally, cavitation bubble collapses generate the noise shock wave, material damage, or flashes of light. Therefore, a fraction of condensation energy may convert to another type of energy. According to these reasons, the influence of heat input in condensation in heat source S_h was investigated, with an adjusting constant c_q as shown in Eq. (2)

$$S_h=-mL=-Lm^{+}-c_qLm^{-}=h_e+c_qh_c. \tag{2}$$

Numerical investigation shown that the heat input by condensation adjusting to its 80% ($c_q = 0.8$) suit the homogeneous cavitation model with a satisfactory prediction of temperature field compare to Hord's experimental data. Comparing with the existing experimental data, the pressure distribution was well reproduced by any thermal model, but the temperature distribution was better improved only in present simplified thermodynamic model as shown in Fig.1.

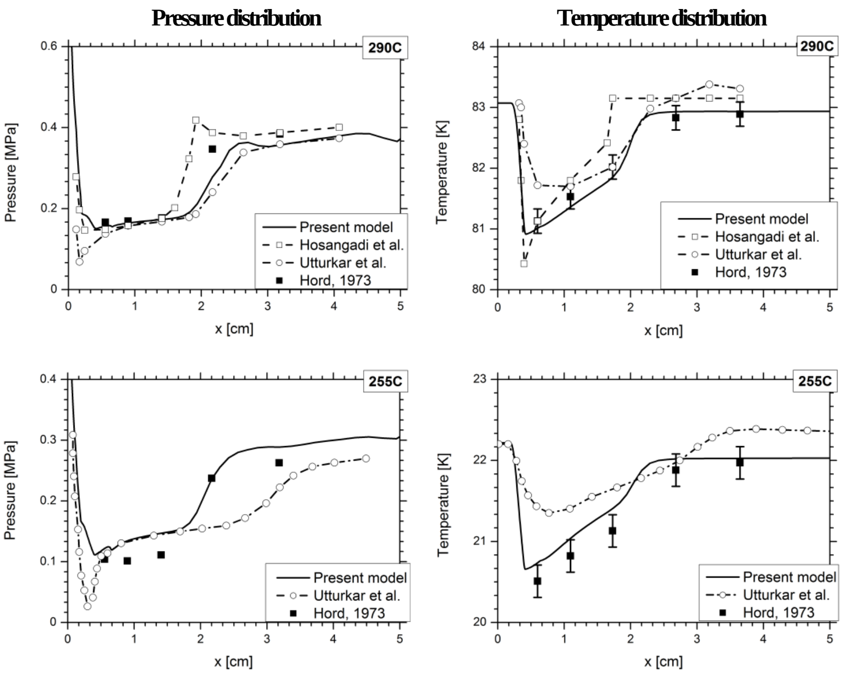

Fig. 1 Comparison of pressure and temperature distribution between present model and existing model for runs 290C in LN_2 and 255C in LH_2

Chapter 4: Numerical study of cavitation flow in hot water up to 90°C

In this chapter, the thermodynamic effect in water cavitation at temperature up to 90°C was clarified by both experimental and numerical study.

Regarding to experiment investigation, the NACA0015 hydrofoil was used as a cavitator. The highly accurate thermistor probes were used to measure the temperature depression inside cavity, which was increased with the increase of water temperature. When freestream velocity increased, the temperature drop was decreased that agrees with the scaling law analysis based on nondimensional thermodynamic parameter $\sum^{*}$.

The numerical simulation was performed based on the experimental data. The satisfactory prediction with experimental data in both cavity aspect and temperature depression was produced by present simplified thermodynamic model.

Importantly, the suppression effect did not appear in water cavitation at temperature up to 90°C. In that, the cavity length was longer when freestream temperature increased in both experimental visualization and numerical simulation.

Chapter 5: Numerical study of cavitation flow in hot water up to 150°C

In this chapter, the thermodynamic effect of cavitation in water with temperature from 120°C to 150°C, which have similar thermodynamic parameter $\sum$ to LN_2, was numerically clarified using present simplified thermodynamic model and present homogeneous model. The Abuaf's experimental data of converging-diverging nozzle flow was selected for investigation.

Regarding to the results, the flow field such as mass flow rate and cross-section averaged parameter was reliable reproduced compare with Abuaf's experimental data. The better prediction of vapor void fraction distribution was reproduced in present simulation compare with the Liao's numerical data using two-fluid model as shown in Fig. 2. It indicates the broadly applicable of present simplified thermodynamic model for different flow fields and fluids.

By comparing the numerical vapor void fraction distribution, the result indicated that the suppression effect, which was not visible in water at 90°C, is appeared when the water temperature increase from 120°C to 150°C.

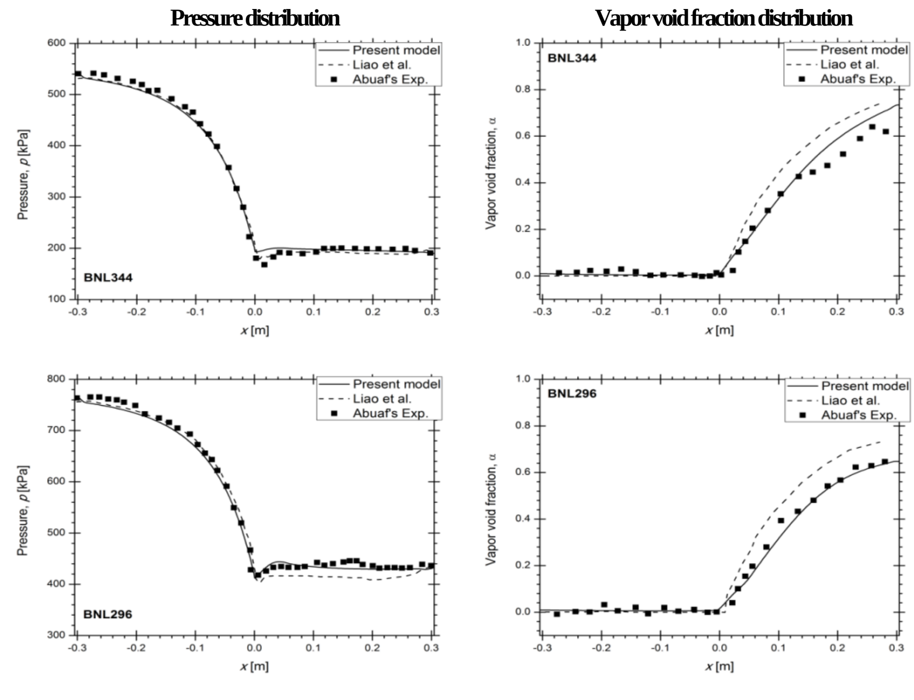

Fig. 2 Comparison of pressure and vapor void fraction distribution along nozzle between present model, Liao's numerical data, and Abuaf's experimental data in case BNL344 and BNL296

Chapter 6: Discussion of thermodynamic effect in Cryogenic fluid

In this chapter, the applicable of the scaling law parameters (B-factor parameter, thermodynamic parameter $\sum$, and nondimensional thermodynamic parameter $\sum^*$), which usually used to predict the thermodynamic effect of cavitation, was investigated for cryogenic liquid based on the Hord's experimental data and present numerical study of LN_2 and LH_2 cavitation. According to analysis, these parameters well predicted the degree of thermal effect for LN_2. For LH_2, as in Fig. 3, the degree of thermal effect was reasonable predicted by $\sum$, but not for $\sum^*$. The trend of temperature depression changed unconditionally with $\sum^*$. Since the parameters $\sum^*$ was derived with the laminar thermal boundary layer assumption. For the real application, the turbulent heat transfer has to be considered in the duration of heat transfer in high Reynolds flow like LH_2 flow. Additionally, through numerical analysis with B-factor parameter, it indicated that thermal equation that can solve the temperature field do need for investigating the thermal effect in cryogenic cavitation.

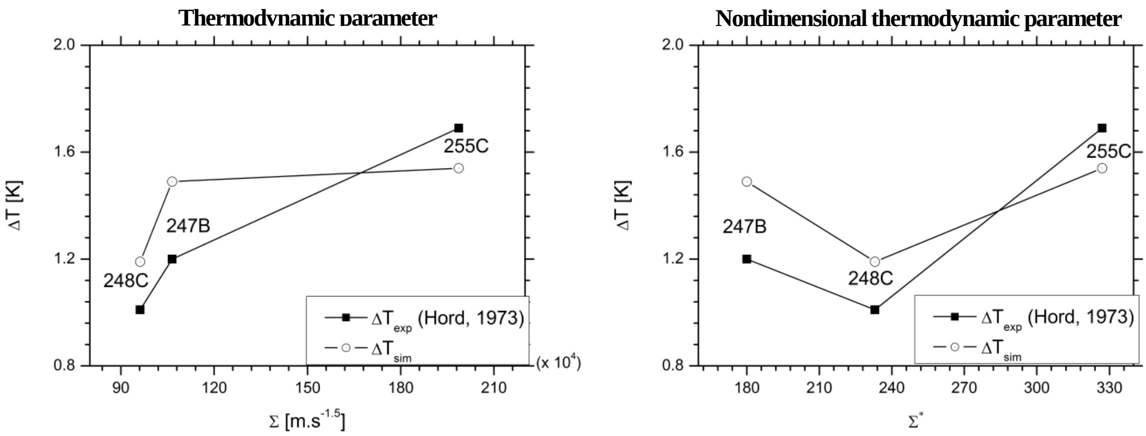

Fig. 3 Trends of maximum temperature depression inside cavity in present numerical simulation ΔT_{sim} and Hord's measured temperature drop ΔT_{exp}, versus thermodynamic parameter $\sum$ and $\sum^*$ for LH_2

Chapter 7: General conclusions

The founding in this thesis is concluded. In this study, following result and knowledge were obtained.

1. A simplified thermodynamic model for homogeneous cavitation model expressed for ρT as conservative variable was proposed.
2. The heat source concerning the latent heat of phase change was explicitly appeared. The heat input in condensation was adjusted to 80% ($c_q = 0.8$) to suite homogeneous cavitation model.
3. The thermodynamic effect on cavitation could numerically be predicted. Satisfactory prediction with experimental data was reproduced in numerical simulation with present simplified thermodynamic model for different flow fields and fluids such as LN_2, LH_2, and wide range water temperature.
4. The popular scaling law parameter such as nondimensional thermodynamic parameter $\sum^*$ failed to predict the degree of thermal effect in high Reynolds LH_2 flows. It suggested that the turbulence heat transfer has to be included in derivation of such parameter.