Effects of physical properties on thermo-fluids cavitating flows

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Abstract: The aims of this paper are to study the thermo-fluid cavitating flows and to evaluate the effects of physical properties on cavitation behaviours. The Favre-averaged Navier-Stokes equations with the energy equation are applied to numerically investigate the liquid nitrogen cavitating flows around a NASA hydrofoil. Meanwhile, the thermodynamic parameter \( \Sigma \) is used to assess the thermodynamic effects on cavitating flows. The results indicate that the thermodynamic effects on the thermo-fluid cavitating flows significantly affect the cavitation behaviours, including pressure and temperature distribution, the variation of physical properties, and cavity structures. The thermodynamic effects can be evaluated by physical properties under the same free-stream conditions. The global sensitivity analysis of liquid nitrogen suggests that \( \rho_v, C_l \) and \( L \) significantly influence temperature drop and cavity structure in the existing numerical framework, while \( \rho_v \) plays the dominant role when these properties vary with temperature. The liquid viscosity \( \mu_l \) slightly affects the flow structure via changing the Reynolds number \( R_e \) equivalently, however, it hardly affects the temperature distribution.

1. Introduction

Cavitation is a phase-change phenomenon that occurs in liquids when the local pressure drops below the saturated vapor pressure, this phenomenon is usually assumed to be an isothermal process [1, 2]. However, the isothermal hypothesis is no longer valid in thermo-fluids cavitation for their thermosensitive properties. When cryogenic cavitation occurs, the temperature drop \( \Delta T \) inside the cavity changes the temperature-dependent physical properties, and then cavitation dynamics is affected [3].

The cryogenic cavitation behaviours have been investigated as early as 1956 [4]. Based on a simple heat balance between two phases, Stahl et al. [4] introduced a B-factor to estimate temperature drop during phase-change process. Hord [5, 6] conducted comprehensive experiments on cavitation with liquid nitrogen and hydrogen under different conditions. Temperature and pressure data were measured at five locations on hydrofoil and ogive models, which have been commonly employed for numerical validation for cryogenic cavitation [3, 7-9].

Recently, Rodio et al. [7] modified the Rayleigh-Plesset equation by the addition of a term for convective heat transfer at the interface between the liquid and the bubble to assess the thermal effects. Experimental visualizations [5, 6] have clearly indicated a mushy nature of the cryogenic cavity. This salient feature of cryogenic cavitation was adapted into the derivation of the interfacial dynamic-based model (IDM) to yield a Mushy IDM [3]. Huang et al. [8] validate a thermodynamic cavitation model based on bubble dynamic equation and calibrate the parameters of the cavitation model for liquid hydrogen. Zhu et al. [9] developed an effective computational strategy to simulate cryogenic cavitation by implementing the “Schnerr-Sauer cavitation model”, coupled with the energy equation.
Although the cryogenic liquid cavitating flows have received much attention in the past years, the effects of fluid physical properties on cavitation behaviours are still not well understood. The present works are to study the thermo-fluid cavitating flows and to evaluate the effects of physical properties.

2. Governing equations and numerical approaches

2.1. Governing equations

The governing equations for thermo-fluid cavitation under the homogeneous multiphase flows consist of the continuity, momentum, enthalpy, and cavitation model equations are given in Ref. [3, 8, 9].

\[ \dot{m}^+ = \frac{C_{\text{dest}} \cdot \alpha_l \cdot \rho_l \cdot \min(p - p_v(T), 0)}{t_c \cdot \rho_v \cdot (0.5 \rho U^*_C)}, \quad \dot{m}^- = \frac{C_{\text{prod}} (1 - \alpha_l) \cdot \max(p - p_v(T), 0)}{t_c \cdot (0.5 \rho U^*_C)} \]

\[ C_{\text{dest}} \text{ and } C_{\text{prod}} \text{ are two empirical coefficients, defined as } C_{\text{dest}} = 3.8, \quad C_{\text{prod}} = 20 \text{ respectively, } t_c \text{ is the reference time scale (} t_c = L_c / U^*_C). \]

\[ \alpha_l \text{ is liquid volume fraction, } p_v \text{ is the saturated vapor pressure.} \]

The computations are performed by using the CFD code CFX to solve the Navier-Stokes equations. The \( k-\omega \) SST (Shear Stress Transport) turbulence model is used in simulating the cavitating flows [11].

2.2. Numerical setup and description

The numerical predictions are compared with the experimental measurements around a NASA hydrofoil in the liquid nitrogen [5]. The computational domain and boundary conditions are shown in figure 1. A no-slip wall is imposed on the hydrofoil surface, and no-slip symmetry is imposed on the side boundary, the lower side of the hydrofoil is not included in the domain because of its symmetry, the inlet velocity, temperature and the outlet pressure are set based on the experimental data. The thermo-sensible properties are updated from the NIST data base [12] throughout the course of computations. The mesh is composed of 19,000 elements with 220 structured elements across the foil boundary layer.

\[ \text{Figure 1. 2D computation domain and boundary conditions} \]

3. Results and discussion

3.1. The characteristics of Thermo-fluid cavitating flows

The thermodynamic parameter \( \Sigma \) defined by:

\[ \Sigma = \frac{\rho_v^2 L}{\rho_l^2 C_v T_c \sqrt{\varepsilon_i}}, \quad \varepsilon_i = \frac{K_i}{\rho_l C_l} \]

is introduced to evaluate temperature change with varying bubble diameter and is crucially important in determining the bubble dynamic behaviour [1]. Here, \( \rho \) is the density, \( L \) is the latent heat of vaporization, \( C \) is the specific heat at constant pressure, \( \varepsilon \) is the thermal diffusivity (works in unsteady heat transfer process) and \( K \) is the thermal conductivity. The suffixes \( v \) and \( l \) indicate vapor and liquid phase. The liquid/vapor density ratio affects cavity size directly, meanwhile, larger latent heat \( L \) and smaller specific heat \( C \) lead to larger temperature drop \( \Delta T \) during the phase change process.

The variations of the parameter \( \Sigma \) for some thermo-fluids are illustrated in figure 2 based on the NIST data base [12], the values increase with increasing temperature. The values are relatively large for hydrogen and helium through the whole temperature range, which indicates strong thermodynamic effects. The values for nitrogen, oxygen and methane are similar to a certain extent, except that the value for the oxygen is extremely small when the temperature is close to its thermodynamics triple point. As to the water, the value is relatively small when the temperature is low, that is why the temperature change (thermodynamic effects) could be ignored in room temperature water. However, the value increases quickly, the magnitude of the value for the water is almost the same as nitrogen.
when temperature is close to 350K. It indicates that the thermodynamic effects on cavitating flow can be evaluated by physical properties under the same free-stream conditions.

Using the numerical method mentioned above, the liquid nitrogen cavitating flow (Case 290C in Ref. [6]) which shows quintessential characteristics of thermo-fluid cavitation behaviours [3, 7, 9] is calculated, it is selected to aid the thermo-fluid characteristic and numerical validation. Significant differences between the thermal and isothermal solutions are illustrated in figure 3, the thermal energy solution can consistently capture the main features of both temperature and pressure profiles, which shows better agreement with the experimental data. The temperature inside the cavity in figure 3(a) depresses due to evaporative cooling, and then the local saturated vapor pressure depresses, that is why the value of $p-p_v(T_{\infty})$ in figure 3(b) is below zero in the cavity region. It is observed that a slight temperature rise above the reference temperature at the rear of cavity, which is attributed to the release of latent heat during the condensation process. Overall, thermodynamic effects significantly affect the thermo-fluid cavitation behaviours. The temperature change during the phase-change process causes the variations of thermo-sensible properties (especially the vapor pressure and density), and then the reference free-stream conditions are changed equivalently, resulting in the change of cavity structure.

3.2. Assessment of the physical properties
As previously discussed, thermo-sensible physical properties and temperature drop significantly influence the cavitation behaviours. In this section, the properties of liquid nitrogen are characterized by surrogate-based global sensitivity analysis and then the weights of each variable are evaluated. Physical properties like liquid density $\rho_l$ and saturated vapor pressure $p_v$ could directly impact the $\sigma_{\infty}$, and hence they are kept constant. Thermal diffusivity $\alpha$ is not taken into consideration due to the steady computation. Since temperature change is small in cavitating flow, thermal conductivity $K$ is ignored either. The vapor density $\rho_v$ affects the mass transfer process, liquid and vapor heat capacity $C_l$ and $C_v$ influence the temperature change, and latent heat $L$ determines the energy of release during the phase change. Therefore, these four physical properties $\rho_v$, $C_l$, $C_v$, $L$ are chosen as design variables primarily, keeping $Re$ and $\sigma_{\infty}$ constant for the Case 290C. Secondly, properties like liquid and gas viscosities which influence the flow structure are taken into consideration. To keep the computational expense reasonable, these properties are perturbed within ±10% as listed range 1 in table 1, it is equal for them to influence the objective. The performance of the cavitation behaviours is characterized by the predicted cavity area and the maximum temperature drop. Based on Case 290C, the responses are evaluated by using CFD simulations at 80 data points selected via Face-centered Cubic Composite Design (FCCD) and Latin Hypercube Sampling (LHS) experimental designs and the weighted average surrogate model (WAS [13]) are constructed for approximation of response.

| Variables | $\rho_v$ | $L$ | $C_l$ | $C_v$ | $\mu_l$ | $\mu_v$ |
|-----------|---------|-----|-------|-------|---------|---------|
| Range 1   | ±10%   | ±10%| ±10%  | ±10%  | /       | /       |
| Range 2   | ±13.40%| ±1.13%| ±0.50%| ±1.28%| ±5.71%  | ±2.09%  |

Figure 4 evaluates the weights of each variable via global sensitivity analysis as pie-charts, as illustrated in figure 4(a), $C_l$ and $L$ are exceedingly significant for the cavity area, while $\rho_v$ has less contribution, and $C_v$ is the least influential parameter within the four variations. Figure 4(b) illustrates the percentage contribution for maximum temperature drop $\Delta T_{max}$, it is observed that the weights of
each variable are almost the same as that in figure 4(a). These observations indicate that thermodynamic effects play the dominant role in the cavitation behaviours when $\sigma_\infty$ and $Re$ are kept constant, it could significantly affect flow structure and temperature distribution.

As previously described, properties $C_l$, $L$ and $\rho_v$ have a significant influence on cavity structure, however, these properties vary differently with changing temperature. $C_l$, $C_v$ and $L$ change slowly while $\rho_v$ has higher slope of saturation curve with increasing temperature. According to the relative change ratio between each variable when liquid nitrogen temperature is 83.06K, a new range of variables named Range 2 is designed and the liquid and gas viscosities are also considered, as listed in table 1, $\rho_v$ changes a lot while other variables change a little.

The weights of each variable with the new range are shown in figure 5, which are completely different from the range 1. For the cavity area, $\rho_v$ accounts for 66.2%, $L$ and $\mu_l$ affect the cavity area slightly while $C_l$ which significantly influence the cavity area in the range 1 as well as $C_v$ and $\mu_v$ could be ignored. It is observed in figure 5(b) that $\rho_v$ plays the leading role on temperature drop, while other variables do not have noticeable contribution. It indicates that the variation of these properties could be ignored when temperature is changing. The method and results can be beneficial to select properties which should vary with temperature in thermo-fluid cavitating flows.

4. Conclusions

In summary, the thermodynamic effects significantly affect the thermo-fluid cavitating flow, including pressure and temperature distribution, the variation of physical properties, and cavity structures. Thermodynamic parameter $\sum$ suggests that the thermodynamic effects can be evaluated by physical properties under the same free-stream condition. $\rho_v$, $C_l$ and $L$ could significantly affect temperature drop and cavity structure in the existing numerical framework. The vapor density $\rho_v$ plays the dominant role when properties vary with temperature. The liquid viscosity $\mu_l$ slightly affects the flow structure via changing the $Re$, however, it hardly affects the temperature distribution. The results are beneficial to select properties which should vary with temperature in thermo-fluid cavitating flows.

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