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Numerical investigation of thermo-sensitive cavitating flows in a wide range of free-stream temperatures and velocities in fluoroketone

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ABSTRACT

The objectives of this paper are to validate an existing numerical modeling framework for fluoroketone and investigate the dynamic evolution of thermo-sensitive cavitating flows. The cavitating flows around a NACA0015 hydrofoil with chord length $C_o = 50.8$ mm and angle of attack $\alpha_0 = 10$ deg in a wide range of temperatures and velocities in fluoroketone are numerically investigated. Three thermal parameters, including nominal temperature drop ΔT^*, thermodynamic parameter Σ and C-factor, are applied to assess the thermodynamic characteristic of fluoroketone. It is found the thermodynamic effects on cavitating flows for fluoroketone at 373 K and nitrogen at 83.06 K are similar under the same reference cavitation number and Reynolds number. It indicates thermal parameters C-factor could accurately predict the extent of thermodynamic effects. General agreements are obtained between the numerical results and the experimental measurements, including the pressure distribution and cavity structures. The numerical results show that there are two typical cavitation dynamics in varying temperature fluoroketone under the same free-stream velocity and cavitation number. As the free-stream temperature increases, cavity area increases to the maximum at the transition temperature and then decreases, the dominant frequency significantly increases when the temperature reaches its transition point. Further analysis indicate that the liquid/vapor density ratio D dominates the change of the cavitation dynamics when temperature is below the transition temperature, and the cavity tends to be mushier and longer with the increasing temperature during this temperature range. However, the thermodynamic effects, which could suppress the development of the cavitating flow, dominate the change of the cavitation dynamics when temperature is above the transition temperature. For free-stream velocity $U_\infty = 9.6$ m/s, which has been experimentally investigated in the reference experiment, the transition temperature for thermo-sensitive cavitation is 318 K (±2 K) and the maximum temperature drop ΔT_{max} is approximately 0.82 K under this condition. For varying free-stream velocity, the increasing velocity could suppress the thermodynamic effects, and hence the transition temperature increases with the increasing velocity under the same flow conditions.

1. Introduction

Cavitation is a dynamic phase-change phenomenon that may occur in a variety of fluid machinery including turbines, pumps and propellers, often leading to the vibration, noise, loss of performance and possible physical damage. Cavitation in room temperature water is widely investigated in the past decades and usually assumed to be an isothermal process [1–5]. However, the isothermal hypothesis is no longer valid in thermo-fluids because of their significant thermodynamic characteristics. The so-called thermo-fluids mean the fluids are thermo-sensitive during the phase-change process. When cavitation occurs in thermo-fluids, temperature change caused by evaporation cooling or condensation heating around the cavity region is significant because of their small liquid/vapor density ratio. Moreover, the temperature-dependent physical properties of thermo-fluids are sensitive to temperature, and then the local flow is altered significantly. Typical thermo-fluids include cryogenic fluids, refrigerant and high temperature water [6–9]. The investigation of cavitating flows in thermo-fluids has practical significance for superconductive magnets to be used in high energy physics accelerators, cryogenic systems of space telescopes, fuel supply systems for liquid rocket engines and the field of electronics cooling [10–14].

The thermodynamic effects on cavitation were firstly investigated by Stahl and Stepanoff [15]. They introduced a B-factor method to estimate the temperature drop during phase-change process based on a simple heat balance between these two phases.

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Nomenclature

ρ	density
t	time
U	velocity
p	pressure
μ	dynamic viscosity
v	kinematic viscosity
h	enthalpy
f	mass volume fraction
L_{ev}	latent heat
Pr	Prandtl number
α	volume fraction
m^+	condensation rate
m^-	evaporation rate
r_b	bubble radius
M	Moore molecule weight
R	liquid or gas constant
T	temperature
C	heat capacity
λ	thermal diffusivity
C_o	chord length
α_0	angle of attack
σ	cavitation number
C_p	pressure coefficient
R_e	Reynolds number
V	volume
ΔT	actual temperature drop
ΔT^*	nominal temperature drop
B	B-factor
Σ	thermodynamic parameter
K	thermal conductivity
k	turbulence kinetic energy
D	liquid/vapor density ratio
A	area

Subscripts

l	liquid phase
v	vapor phase
∞	reference
m	mixture
tur	turbulent
lam	laminar
cav	cavity
c	cross-section of the hydrofoil
max	maximum
i, j, k	directions of the Cartesian coordinates

An appropriate thermodynamic parameter Σ was conducted by Brennen [1] to assess the thermodynamic effect by incorporating it into the Rayleigh-Plesset equation for cavitation bubble dynamics. This parameter proposes a criterion to determine if cavitation process is thermo-sensitive or not. To directly investigate cavitating flows in thermo-fluids, Hord [16,17] measured temperature and pressure data around hydrofoil and ogive models in liquid nitrogen and liquid hydrogen under a lot of flow conditions, which is the most popular and detailed experimental data so far. Holl et al. [18] conducted comprehensive experiments about developed cavitation in water and Freon 113 under different sets of inlet velocity and temperature conditions with four test models. Temperature and pressure data were also obtained for zero- and quarter-caliber ogives.

Thermodynamic effects on cavitating flows have not been fully investigated due to experimental difficulties handling cryogenics. Recently, Franc et al. [7] investigated the cavitation instabilities of refrigerant R-114 in an inducer. They found that the development of blade cavitation was suppressed by thermodynamic effects at higher reference temperature. Cervone et al. [8] carried out experiments in water around a NACA 0015 hydrofoil at various cavitation numbers and free-stream temperatures to investigate the thermodynamic effects on cavitation instabilities and dynamics. Kelly and Segal [19,20] investigated the cavitating flows of fluoroketone, chosen as a surrogate for cavitating liquid cryogens, in a wide range of velocities, cavitation numbers, angle of attack and temperatures. Unsteady surface pressures and high speed imaging offer both quantitative and qualitative insight into the physical process of thermal cavitation. Planar laser imaging offers an instantaneous look inside the cavity and at the behavior of the boundary between the cavity region and liquid. Although Kelly has conducted experiments in fluoroketone under a lot of conditions, the dynamic evolution of fluoroketone cavitating flows, the temperature change inside the cavity and the thermodynamic effects on cavitation dynamics in a wide range of temperatures and velocities are still not well understood.

Due to the limitations of experimental techniques, numerical methods have been developed to investigate the cavitating flows. Modeling of cavitation model plays a significant role in the numerical methods of cavitating flows. Generally, most cavitation models assume the multiphase region to be homogenous, and apply either a transport equation [21–23] or a barotropic equation of state (EOS) [24] to solve the variable density inside the cavity during the cavitation process. Colombet et al. [25] investigated closure laws for the description of interfacial mass transfer in cavitating flows under thermal regime. They found that modeling of interfacial heat transfer depends on a Nusselt number which is a function of the Jakob number and of the bubble thermal Péclet number. Jakob number variation is influenced by phasic temperature difference and density ratio variation. As the physical properties significantly affect cavitation dynamics, the major challenges in using these cavitation models for thermo-fluids cavitating flows are to form the dynamic mass and heat transfer process and to consider the temperature change.

Modeling of turbulence model is crucial for simulating cavitating flow because the cavitating flow is basically unsteady in nature. Mani et al. [26] numerical investigated four canonical problems (cavitation individually occurs in flows with a bluff body pressure drop, adverse pressure gradient, blade passage contraction, and rotation.) under the Reynolds Average Navier–Stokes (RANS) framework. They found that the choice of turbulence model plays a significant role in the prediction of the phase distribution in the flow. And the cavitation models of barotropic equation of state (EOS) are far more sensitive to the turbulence closure than the transport-based models. As the current RANS approaches with eddy viscosity turbulence models can not accurately capture the unsteady characteristics of cavitating flows due to the overprediction of turbulent eddy viscosity [24,27–29]. Large Eddy Simulations (LES) which could accurately capture the unsteady behaviors are developed to predict unsteady cavitating flows [30–33], however, LES requires quite significant computational resources. And hence, some modified or hybrid turbulence models have been developed to strike a compromise. Such as the density corrected model (DCM) [6,27–29], the Partially-Averaged Navier-Stokes (PANS) model [34] and the filter-based models (FBM) [35].

Two typical cavitation dynamics from classical to thermo-sensitive cavitation have been observed and the transition