Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(6):987-999
DOI: 10.1016/S1001-6058(16)60813-2
www.sciencedirect.com/
science/journal/l0016058

Numerical investigation of unsteady sheet/cloud cavitation over a hydrofoil in thermo-sensitive fluid *

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(Received July 12, 2017, Revised October 14, 2017)

Abstract: The sheet/cloud cavitation is of a great practical interest since the highly unsteady feature involves significant fluctuations around the body where the cavitation occurs. Moreover, the cavitating flows are complicated due to the thermal effects. The present paper numerically studies the unsteady cavitating flows around a NACA0015 hydrofoil in the fluoreketone and the liquid nitrogen with particular emphasis on the thermal effects and the dynamic evolution. The numerical results and the experimental measurements are generally in agreement. It is shown that the temperature distributions are closely related to the cavity evolution. Meanwhile, the temperature drop is more evident in the liquid nitrogen for the same cavitation number, and the thermal effect suppresses the occurrence and the development of the cavitating flow, especially at a low temperature in the fluoroketone. Furthermore, the cavitating flows are closely related to the complicated vortex structures. The distributions of the pressure around the hydrofoil is a major factor of triggering the unsteady sheet/cloud cavitation. At last, it is interesting to find that one sees a significant thermal effect on the cavitation transition, a small value of $\sigma/2\alpha$ is required in the thermo-sensitive fluids to achieve the similar cavitation transition that occurs in the water.

Key words: Sheet/cloud cavitation, thermal effects, dynamic evolution, thermo-sensitive fluids

Introduction

The cavitation usually occurs when the pressure in a liquid drops below the vapor pressure in the local thermodynamic state[1,2]. In general, the cavitation is unavoidable and will lead to undesirable effects, such as noise, vibration and surface erosion. A comprehensive understanding of the flow mechanism of the sheet/cloud cavitation is important for the related engineering design. The production of the vapor from the cavitation absorbs the latent heat of the evaporation from the surrounding liquid, resulting in a temperature depression inside the cavity. This phenomenon is called the thermal effects of the cavitation[3]. Usually, the thermal effects of the cavitation occurs in the room temperature water can be ignored and the cavitation may be assumed to be an isothermal process[4-6]. The so-called thermo-fluid means that it is thermo-sensitive, with a rapid vapor pressure variation and a low liquid to vapor density ratio, that would have substantial thermal effects due to the cavitation. Then the local flow is altered significantly and becomes more complicated[7]. The typical thermo-sensitive fluids include the liquid hydrogen, the liquid nitrogen and the liquid oxygen, which are proposed as the propellants for rockets and other aerospace equipment. Hence, the unsteady sheet/cloud cavitation with the thermal effects involved is an important issue.

During the past few decades, considerable efforts have been made to study the thermal effects in the cavitating flows. As early as 1956, Stahl and Stepanoff[8] introduced a *B*-factor method to estimate the tempera-

* Project supported by the National Natural Science Foundation of China (Grant Nos. 51709042, 11672094, 51522902, 51639003 and 51679037), the Fundamental Research Funds for the Central Universities (Grant Nos. DUT16RC(3)085, DUT17ZD233) and the Natural Science Foundation of Heilongjiang Province (Grant No. A201409).
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ture drop induced by the thermal effects during the phase change process. Sarosdy and Acosta[9] conducted cavitation experiments in the water and the Freon. They found that the cavity in the Freon was indistinct and frothy, while the cavity formed in the water was relatively clear. Hord[10,11] carried out the most popular and detailed experiment in the liquid hydrogen and nitrogen, and obtained the cavity length, the temperature drop and the pressure distribution under various flow conditions. Thermal effects on the cavitation have not been effectively investigated due to the experimental difficulties. Recently, Franc et al.[12] investigated the instabilities of the cavitating flow around the inducer blades in the Freon R-114. They found that the onset of the blade cavitation was delayed and suppressed due to the thermal effects. Niiyama et al.[13] carried out experiments around a hydrofoil in the liquid nitrogen, and obtained several features of the thermal effects. They found that the mean thickness of the liquid was small, caused by the suppression of the temperature diffusivity. Because of the limitation and the safety problems of the cavitating flow experiment in cryogenic fluids such as the liquid hydrogen and nitrogen, Gustavsson et al.[14], Kelly and Segal[15,16] chose the fluoreketone as a surrogate for the cavitating liquid cryogens to investigate the cavitating flows in a wide range of cavitation numbers, temperatures and angles of attack. Unsteady cavity shapes and pressures were obtained for a qualitative and quantitative insight into the thermal cavitation. Although considerable experiment results were obtained, the thermal effects of the cavitation dynamics in different fluids, the dynamic evolution of unsteady cavitating flows, and the transition characteristics in thermo-sensitive fluids are still not well understood.

More numerical simulations are necessary to investigate the cavitating flows with thermal effects involved to fill the gap due to the lack of the measurement data and experiment techniques. Cavitation models play a significant role in the accuracy of the prediction for the cavitating flows. Generally, the present cavitation models based on the homogeneous flow method are widely used for the cavitating flows. These cavitation models are usually established as a mass/volume fraction equation, with the mass transport processes being expressed as the evaporation and condensation rates, such as the models proposed by Singhal et al.[17], Merkle et al.[18], Kunz et al.[19] and Zwart et al.[20]. Recently, Hosangadi and Ahuja[21] used the Merkle cavitation model to simulate the cavitating flows in the liquid nitrogen and hydrogen, they found that the thermal depression was enhanced at lower velocities, meanwhile, they suggested using lower parameter values for the cavitation model. Tseng et al.[22,23] investigated the modeling for the cryogenic cavitation with refined cavitation model parameters. They found that the evaporative cooling reduced the cavitation intensity and resulted in a shorter length than that under isothermal conditions. Yu et al.[24] developed a new cavitation model with consideration of the viscous effect to simulate the cavitating flow in the water in cases of large liquid temperature variation. Huang et al.[25] used a thermal cavitation model to simulate the 2-D cavitating flows in the liquid hydrogen, and evaluated the sensitivity of the response to the cavitation model parameters and the temperature-dependent material properties. Sun et al.[26] extended a cavitation model based on the transport-based cavitation model, and more accurate predictions of the thermal effects during the cavitation process were obtained. Chen et al.[27] considered the heat transfer effect during the phase transfer process, in a wide range of free-stream temperatures and velocities in the fluoroketone. These numerical studies provide some insight into the cavitating flows of thermo-sensitive fluids.

The cavitation is basically unsteady in nature and it is accompanied by a multi-scale turbulent flow, furthermore, the thermal effects will increase the difficulty in the simulations of cavitating flows in thermo-sensitive fluids. Hence, the methods of turbulence modeling are important. Mani et al.[28]. numerically investigated the turbulence modeling of cavitating flows in turbopump inducers by the Reynolds averaged Navier-Stokes (RANS) method. They found that the cavitation prediction was related to the choice of the turbulence models, and the sensitivity of the turbulence model was strongly dependent on the types of cavitating flows. Zhu et al.[29] applied the large eddy simulation (LES) method to investigate the interactions of the vortices, and the thermal effects of cavitating flows in the liquid hydrogen, and a special cavitation shedding mechanism was found to reveal the complex dynamic feature of the thermal effects. Due to the over-prediction of the turbulent eddy viscosity of the RANS methods, the unsteady characteristics cannot be effectively captured. However, the LES approach is computationally too expensive. Hence, some approaches are developed to combine the advantages of the RANS and the LES. Girimaji[30] developed a hybrid method of the partially averaged Navier-Stokes (PANS) model, which can capture the unsteady features of important scales of the turbulent flow with a minimal computa- tional cost, and it has been successfully applied in various researches of unsteady cavitating flows with reasonable results[31-33].

Generally, the cavitation instability is closely related to the pressure distribution in the cavity closure region. Especially, a high adverse pressure gradient exists at the rear of cavity, and a re-entrant jet will be developed to trigger the cavity shedding[34-36]. More recently, in addition to the re-entrant jet observation, Ganesh et al.[37] found that the bubbly shock