

A Numerical Study on the Effects of Cavitation Number on Cavitating Mixing Layer of Liquefied Natural Gas (LNG) behind a Flat Plate Splitter

Saeed Rahbarimanesh; Joshua Brinkerhoff*

The University of British Columbia, Kelowna, BC, Canada

Abstract

The mutual interaction of shear layer instabilities and phase change in a two-dimensional, unsteady cryogenic cavitating mixing layer is investigated using numerical simulation. The model is developed based on homogeneous equilibrium mixture (HEM) approach in a density-based framework to compute the temperature-dependent cavitation field for liquefied natural gas (LNG). The mixing layer is simulated for vorticity-thickness Reynolds numbers of 44 to 215 and cavitation numbers of 0.1 to 1.1. At the lowest cavitation numbers, steady vapor cavities are initiated on the splitter plate, followed by roll-up of the separated shear layer via the well-known Kelvin-Helmholtz mode. Unsteady, shear-driven cavitation then occurs as vapor cavities nucleate and grow from the low-pressure cores in the rolled-up vortices. As the Reynolds number and cavitation number are varied, thermal effects and baroclinic vorticity production are found to have significant impacts on the mutual interaction of shear-layer instabilities and unsteady cavitation processes.

Keywords: cryogenic cavitation model; unsteady cavitation; LNG; shear layer instability

Introduction

Pressure modulated liquid-to-vapor phase changes (cavitation) is a challenging topic of research in engineering and is a key issue in turbomachinery design. For instance, positive-displacement fuel pumps are significantly degraded by the presence of even a small volumetric percentage of vapor, leading to significant decay in output head and loss of machine efficiency [1]. The complexity of the cavitation phenomenon becomes even more pronounced in the case of cryogenic fluids such as liquefied natural gas. Phase change process in cryogenic fluid systems, where the operating temperature is typically close to the critical temperature of the working fluid, occurs with exchanging substantial thermal effects and abrupt changes in fluid properties, which alter the vapor phase fraction characteristics compared to isothermal fluids. In particular, the cryogenic phase change process involves not only mass transfer effects due to evaporation/condensation, but also heat transfer corresponding to the latent heat of vaporization of liquid phase. Such a behavior, combined with lower liquid to vapor density ratios, causes cryogenic cavitation to experience altered vaporization and condensation rates compared to isothermal cavity structures [2].

In dealing with cavitation on turbomachinery installations two major patterns are frequently observed: 1) attached sheet cavitation, such as steady cavities on the suction side of rotary inducer blades, and 2) unsteady shear-flow cavitation, such as separated cavitating flows in the trailing edge region of rotor blades or tip-clearance cavitation observed in pumps [2,3]. Attached sheet cavity structures, normally initiated as a developing boundary layer on the wall in the case of thermo-insensitive fluids such as water, is often followed by unsteady vortex cavitation which is caused by shedding of vortical structures into the flow downstream of vapor cavities [1]. Continuation of the vortex cavity shedding causes the formation of large-scale vapor clouds downstream of the flow which might be accompanied by re-entrant jets in the near-wall regions. The detached cloud structures consist of bubble-filled large-scale coherent vortices [1,3,4]. In the case of cryogenic cavitation, the vortex-cavity interaction mechanisms can occur simultaneously with temperature-induced phase change (boiling) and thermal gradients that reshape the cavity structures. For instance, temperature decreases around cavity spots due to the exchange of latent heat during vaporization cause these structures to expand and grow. As a result of this temperature drop, saturated vapor pressure in the surrounding liquid around the cavity spots is reduced and delays the expansion rate of cavities compared to the thermo-insensitive cavitation [5]. The physics in cryogenic cavitating flows is thus heavily influenced by interactions between phase instabilities, thermal interactions, and shear layer instabilities, leading to a complex interplay between coherent vortical structures, phase change process, and thermodynamic effects. Moreover, compared with isothermal cavitation, these interactions are further amplified by local temperature fluctuations added to other sources of unsteadiness such as density and pressure variations [6].

*Corresponding Author, Joshua Brinkerhoff: joshua.brinkerhoff@ubc.ca

A number of experimental and numerical studies on unsteady cavitation, mainly focusing on the effect of fluid property variations in isothermal cavitating shear layers of water, have been reported in literatures [3,7,8]. Among these studies, Wang and Ostoja-Starzewski [1] developed a single fluid model with an incorporated LES scheme, using a fifth-order polynomial relationship between density coefficient ratio and pressure coefficient, for weakly-compressible cavitating fluids. Time-dependent sheet/cloud cavitation structures around a NACA0015 airfoil in a range of operating conditions were simulated to illustrate the non-linear interaction between macroscopic vortex motion and microscopic bubble dynamics. More recently, Iyer and Ceccio [9] used particle image velocimetry-laser induced fluorescence experiments to investigate the influence of developed cavitation on a turbulent shear layer flow of water with different range of void fractions. They suggested that the overall formation, growth mechanism, and convection of the primary and secondary vortical structures of the shear layer are not influenced significantly by the presence of the vapor phase. However, an increase of turbulent fluctuations in the center of the cavitating shear layer is observed compared to a baseline non-cavitating case. It is also reported that cavitation has a strong effect on Reynolds stress tensor anisotropy especially in downstream regions where the cross-stream velocity fluctuations and the Reynolds stresses of the cavitating shear layer are reduced in comparison with the non-cavitating case.

Due to lack of knowledge concerning the detailed mechanisms of shear layer instabilities and their correlation with cryogenic phase change processes, the objective of the present research is to explore the nature of these interactions through fundamental numerical simulations of a cryogenic cavitating mixing layer of LNG. The resulting numerical database on the detailed dynamic behavior of LNG cavitating shear flows will aid in characterizing the unsteady interactions of phase instabilities and shear layer instabilities in turbulent two-phase flows at cryogenic conditions. In particular, the present study assesses the influence of cavitation number on the unsteady cryogenic cavitation.

Computational Model

The current study uses a cryogenic cavitation model developed by the authors [10], which is built on the currently-available *cavitatingFoam* solver in the open-source OpenFOAM® libraries. The developed solver employs the homogeneous equilibrium mixture (HEM) approach with a barotropic equation of state in a density-based framework. Baroclinic and thermal effects on the flow field are accounted by solving an enthalpy-based energy conservation equation in conjunction with thermophysical property models that accurately captures the properties of LNG at cryogenic temperatures for a broad range of pressures. In addition, the saturation vapor pressure is made dependent on temperature by using the saturation pressure relationship from the Clausius-Clapeyron equation [4]. An extended merged PISO-SIMPLE algorithm is used to iteratively couple the resulting temperature field to the pressure, velocity, and vapor fraction fields.

Computational Setup

Following the experimental study of Aeschlimann et al. [3], a two-dimensional cavitating mixing layer of LNG behind a flat splitter plate is simulated using the developed cryogenic cavitation solver. The splitter plate has a thickness of 6 mm with a rounded edge of 0.2 mm radius, which is placed in a 300×80 mm² rectangular domain (figure 1). The domain is meshed using 525,700 non-uniform structured 2D elements. The velocity above (U_1) and below (U_2) the splitter is 15.8 m/s and 3.5 m/s, respectively, and three cavitation numbers 0.21, 0.65, and 1 are studied; the cavitation numbers are defined in terms of the low-speed flow pressure at the inlet, correspondingly giving total pressure ratios of 1.094, 1.064, and 1.04 between the high- and low-speed sides. Outlet static pressure is fixed at 4.13 bar. Initial flow field contains only liquid methane (LNG) with operating temperature of 132 K.

Results and Discussion

The temporal evolution of vapor phase fraction and temperature fields for LNG cavitating mixing layer with operating cavitation numbers of 0.21 and 0.65 at time instant $t = 120$ s is depicted in figure 2. Figure 2(a) and (c) show that a steady attached vapor cavity forms in the upper splitter plate boundary layer. Downstream of the splitter plate, the near-wall vorticity quickly rolls-up into discrete vortices owing to the development of Kelvin-Helmholtz instability in the highly-strained braid regions [4,11-13]. Pairing of these counter-rotating vortices occurs within a few wavelengths downstream of the splitter plate, leading to larger-scale structures with twice the streamwise period; this secondary instability is due to the non-uniform acceleration of the primarily-shed structures by the non-

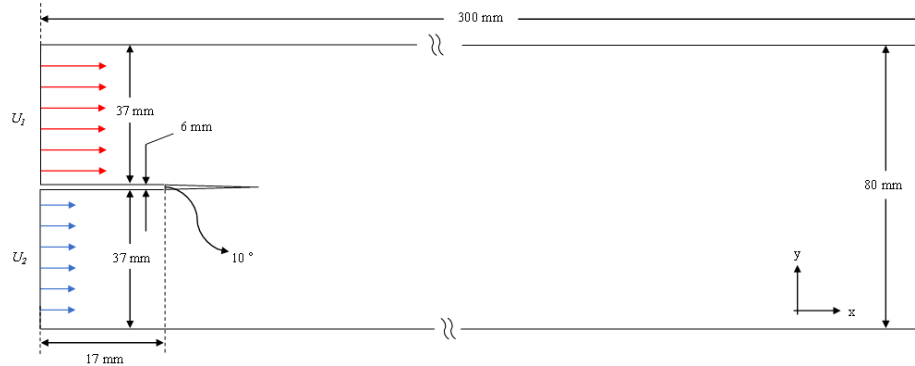


Figure 1: Computational domain

uniform velocity field. A subsequent tertiary pairing also occurs at the lowest cavitation number ($\sigma = 0.21$) by the same mechanism. These observations of the vortical structures are based on the observed coincidence of coherent vortices and vapor cavities. Vapor cavities nucleate in the core of the coherent vortices as the local static pressure reduces due to locally high rotation rate [3,4]. As the secondary and tertiary vortex pairing occurs, the vapor cavities also grow into unsteady cavitation clouds. The growth of unsteady cavitation clouds is sustained by the continual shedding of the shear layer vortices which induce continuous pressure and density fluctuations affecting the size of the cavitating cores [14].

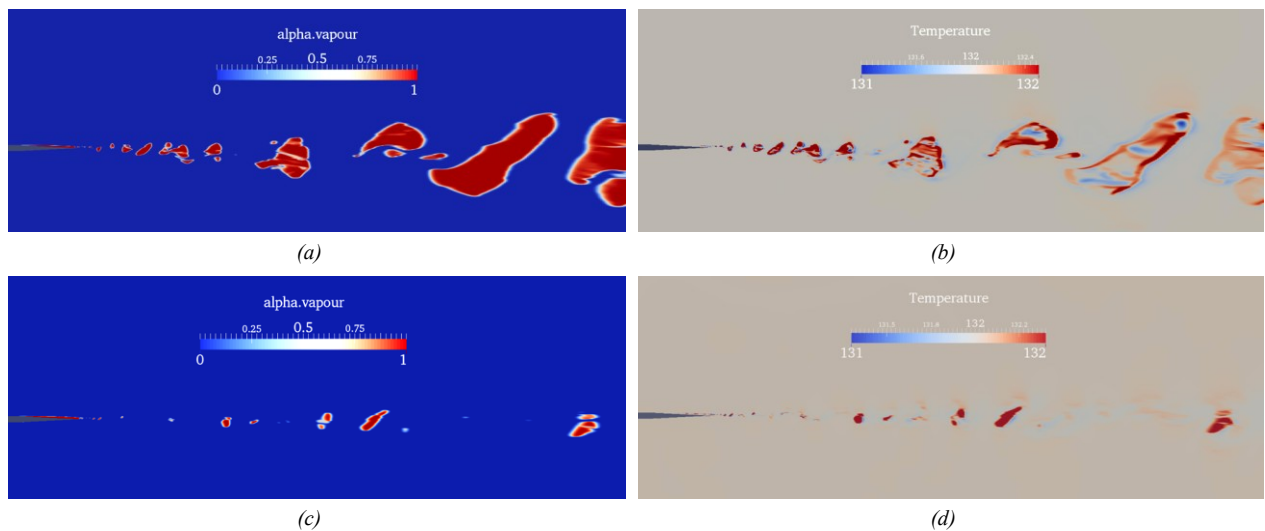


Figure 2: Temporal evolution of cavitating mixing layer of LNG at $t = 120$ s: vapor phase fraction (α) field at cavitation number (a) $\sigma = 0.21$ and (c) $\sigma = 0.65$; temperature field at cavitation number (b) $\sigma = 0.21$ and (d) $\sigma = 0.65$.

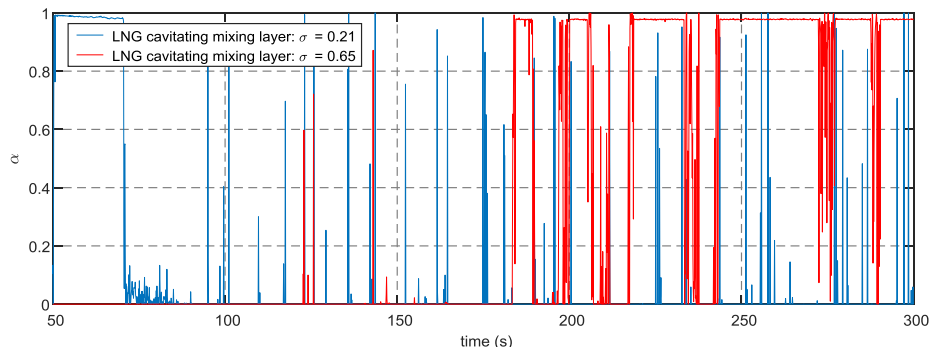


Figure 3: Time history of vapor fraction field (α) of cavitating mixing layer of LNG at the probe placed at $x = 1$ mm and $y = 0$ mm close to the splitter trailing edge; the vapor field fluctuation is shown for two cavitation numbers of 0.21 and 0.65.

In the temperature field (figure 2(b)-(d)), a slight temperature change of ± 1.8 K is observed with high temperature gradients along the liquid/vapor interfaces and the frontal side of cavities. This small variation significantly influences the evolution of the vapor cavities. As vapor spots are generated and grow, the latent heat of vaporization is absorbed from the surrounding liquid causing a temperature drop around the vapor area. Because of the direct connection between temperature and saturation pressure, the drop in temperature decreases the saturation pressure, resulting in an overall delay in the inception and growth rate of the vapor spots [4,10]. This behavior diminishes at higher cavitation numbers, as shown in figure 2(c)-(d), which yields smaller vapor cavities. This suggests that reducing the cavitation number enhances the growth of vapor cavities by increasing the amplification rate of shear-layer instability [3,4,14]. Such a behavior is illustrated in figure 3 by plotting the temporal variation of vapor fraction field at a point 1 mm downstream of the splitter plate ($x = 1$ mm, $y = 0$ mm) for cavitation numbers of $\sigma = 0.21$ and 0.65 . As seen, successive vaporization and collapsing of cavities at lower cavitation number adds additional unsteadiness to the flow and thus fluctuations in the local temperature. The vapor cavities are more strongly affected by temperature variations at lower cavitation numbers. Evaluation of the compressible vorticity transport equation (not shown) indicates that baroclinic vorticity production terms, introduced as a result of temperature dependence of the density field, enhances vorticity production at phase interfaces, leading to higher amplification rates of shear-layer instability of these cavities [4,10].

Conclusion

A cryogenic cavitation solver is used to simulate a cavitating mixing layer of LNG behind a flat splitter plate, aimed at identifying the interaction of shear layer instabilities and phase change in cryogenic fluids. The growth of unsteady cavitation is linked to coherent vortices generated following the roll-up of the shear layer past the splitter plate. For small cavitation numbers, vapor cavities nucleate at the center of the coherent vortices and evolve into large-scale cavity clouds through vortex pairing due to secondary shear layer instabilities. Non-isothermal effects modify the growth of vapor cavities by influencing the shear-layer instability process through introducing baroclinic vorticity generation mechanisms.

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