International Journal of Heat and Mass Transfer 114 (2017) 769–785

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Unsteady pressure fluctuation characteristics in the process of breakup and shedding of sheet/cloud cavitation

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ARTICLE INFO

Article history:
Received 20 February 2017
Received in revised form 28 April 2017
Accepted 2 June 2017
Available online 1 July 2017

Keywords:
Cavitation
Cavity shedding mechanism
Re-entrant flow
Shock wave propagation
Pressure fluctuation

ABSTRACT

The objective of this paper is to investigate the unsteady pressure fluctuation characteristics in the process of breakup and shedding of unsteady sheet/cloud cavitating flows via combined experimental and computational methods. Experiments are conducted in the divergent section of a convergent-divergent channel using a simultaneous sampling technique to synchronize the transient cavitation behaviors and wall-pressure signals. In the numerical simulations, the Zwart cavitation model and the modified RNG k-ε turbulence model are solved, with the compressibility effects of both water and vapor considered. In addition, one-dimensional bubbly shock wave relationship is applied to analyze the process of the vapor fraction discontinuity propagation. Two different types of cavity breakup and shedding existing in the unsteady sheet/cloud cavitating flows are observed, which is induced by re-entrant flow and vapor fraction discontinuity propagation mechanism, respectively. The re-entrant flow generates at the rear of the cavity, moving forward along the wall. When it arrives at the throat, it breaks up the attached cavity, resulting in the cloud cavity shedding. During the process, the wall pressure fluctuation is relatively small. The vapor fraction discontinuity propagation is resulted from the bubbly shock in water/vapor mixture of the sheet/cloud cavity. There is a significant difference of vapor fraction between the pre- and post of the discontinuity. The pre-discontinuity area is almost pure vapor, and the post-discontinuity area consists of water/vapor mixtures with relatively low vapor fraction. During the discontinuity propagation, the pressure peak exists at shock wave front. When the discontinuity arrives at the throat, the void fraction will suddenly decrease, which indicates the low vapor generation rate. Under the convection of the main flow, the attached cavity will be separated from the newly generated vapor, resulting in the attached cavity breaking up and the cavity cloud shedding.

1. Introduction

Cavitation is an abrupt phase change phenomenon that occurs in liquids when the local static pressure drops below the saturated vapor pressure, in a variety of fluid machinery including turbines, pumps and marine propellers [1–3]. Occurrence of unsteady cavitation, especially the periodic breakup and shedding of sheet/cloud cavity, can lead to problems such as pressure fluctuations, sudden changes in loads, vibration, noise, and erosion [4–8]. The inhibition of these instabilities requires detailed understanding of the physical mechanism of unsteady cavitation dynamics [9]. Cavitation is usually assumed to be an incompressible process. However, due to the local void fraction variations in liquid/vapor mixture region, a marked reduction of the speed of sound exists in the unsteady sheet/cloud cavitating flows, which implies that the multiphase flow region is highly compressible [10–13]. It can be expected that in the case of high-speed liquid flows, for example, in pumps or injectors, the local Mach number in the liquid/vapor mixture increases up to 10, whereas it is generally close to 0 outside the mixture [14,15]. This feature of highly compressible in cavity area has a powerful feedback on the cavitation dynamics.

The breakup and shedding mechanism of sheet/cloud cavitating flows has been widely investigated around hydrofoils, axisymmetric bodies and in the convergent-divergent channels [16–18]. The experimental studies have identified the presence of two main mechanisms of unsteady cavitation dynamics, namely re-entrant flow mechanism and shock wave propagation mechanism, and most researchers focus on the re-entrant flow mechanism. The re-entrant flow is mainly composed of liquid which generates at the trailing edge of a sheet cavity and flows upstream along the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.005
0017-9310/

Nomenclature

ρ	density
t	time
U	velocity
p	pressure
μ	dynamic viscosity
v	kinematic viscosity
h	enthalpy
f	mass volume fraction
Pr	Prandtl number
α	volume fraction
m^-	evaporation rate
m^+	condensation rate
R	liquid or gas constant
T	temperature
σ	cavitation number
C_p	pressure coefficient
R_e	Reynolds number
V	volume
k	turbulence kinetic energy

Subscripts

l	liquid phase
v	vapor phase
∞	reference
m	mixture
tur	turbulent
lam	laminar
cav	cavity
max	maximum
$ref\text{-}re$	cycle of re-entrant flow mechanism
$ref\text{-}sh$	cycle of shock wave mechanism
i, j, k	directions of the Cartesian coordinates

solid surface. When the re-entrant flow arrives at the leading edge of the attached cavity, the attached cavity pinches off, rolls up and then sheds downstream as a large scale cloud cavity. The development of a liquid re-entrant flow was firstly observed by Knapp using high-speed video [19]. Furness and Hutton combined the theoretical and experimental studies on the attached cavities in a two-dimensional convergent-divergent nozzle [20]. They initially demonstrated that the re-entrant liquid flow was the cause of the cavity rear part instabilities. To improve the understanding of the re-entrant flow mechanism of partial cavitation instabilities, various experimental studies have been conducted. Kawanami et al. fitted an obstacle on the foil surface to investigate the generation mechanism of cloud cavitation [21]. They found that the obstacle installed on the path of the re-entrant flow greatly depressed the intensity of attached cavity breakup and shedding. Stutz and Reboud employed a double optical probe to measure the flow structure including void fraction, velocity and the sheet cavity structures in a venture-type test section [22,23]. They demonstrated quantitatively the occurrence of a re-entrant flow under the cavity which flows upstream and results in cavity periodically break off. Callenaere et al. investigated the re-entrant flow induced by cavitation instability experimentally on a diverging step, and they found that the pressure gradient and the ratio of the thicknesses of the cavity and of the re-entrant flow are the main parameter influencing the cavitation instability [24]. The relationship between large scale vortex at the rear of the sheet cavity and the re-entrant flow is also investigated Huang et al. [16,25] and Ji et al. [26–28]. The results showed that the large scale vortex motion would cause the reverse pressure gradient near the wall and hence produced the reverse flow.

The experiments conducted by Stutz and Legoupil [29] and Coutier-Delgosha et al. [30] using *X-ray* attenuation method indicated that the void fraction within the cavity can be up to 0.60, verifying that the cavity is not very dense under certain conditions. According to the discussion of variation of speed of sound with void fraction in Brennen [31], it should be noted that the speed of sound within the cavity could experience sharp decrease, resulting in high local Mach number. On the other hand, the collapse of cavitation structure, such as large scale bubble clusters, is supposed to release pressure pulses with large magnitude. Due to the sharp decrease in the speed of sound within the attached cavity, the propagation of pressure pulses is associated with another time scale in the flow, which could have great effect on the cavitation dynamics. This indicates the possibility of the existence of shock wave propagation mechanism of cavitation instabilities. Reisman et al. used high-speed video and unsteady pressure transducers to investigate the large impulsive surface pressures [32], which are of large amplitude and short duration during the rapid collapse of large scale cavitation structure. The similar pressure pulses have also been captured by Leroux et al. [33] and Chen et al. [34]. Combining with the high-speed photo, they demonstrated that several types of propagating structures and shock waves were produced in a collapsing cloud, and they concluded the rapid change in the void fraction was responsible for the dynamics in cavitating flows. Following, Arndt et al. adopted the integrated experimental/numerical investigation to improve the understanding the complex physics in sheet cavitation and the transition to cloud cavitation [35]. They concluded that at high values of $\sigma/2\alpha$ (σ is the cavitation number and α is the angle of attack), the re-entrant flow mechanism dominates the shedding of cloud cavitation while at low values of $\sigma/2\alpha$, bubbly shock wave phenomena dominates. The transition was found to occur at $\sigma/2\alpha$ = 4. Leroux et al. carried out the experimental-numerical collaborative research on the understanding of the mechanisms of the partial cavitation instabilities [36]. They found that two distinct cavity self-oscillation dynamics characterized by two different frequencies were obtained at the angle of 6° and 8°, respectively, and the shock wave produced by the collapse of the large scale cavity cloud was recognized to have significant influence on the growth of the residual cavity. Van Rijsbergen et al. synchronized the measurements of the cavitation image and cavitation acoustics emission to investigate the cavitation collapsing structure and the erosion mechanism on a NACA0015 foil. They concluded that a surface-directed implosion may be enhanced by a pressure wave emitted during the implosion process of bubble cloud [37]. Foeth et al. applied the high-speed camera to study partial cavitation dynamics on a twisted foil. They found that side-entrant flow along the span wise direction in the closure region was a second shedding mechanism. The collision of side-entrant flow pinches off the sheet cavity, resulting in vapor clouds shedding [38]. Li et al. employed the high speed photo and particle image velocimetry (PIV) method to investigate the structures of supercavitating flows [39]. They showed that there exists an evident propagating discontinuity within the supercavity, with sharp change of vapor fraction distribution across the discontinuity, and a strong momentum transfer were measured within the cavity. Recently, Ceccio et al. conducted the experiments to study the mechanism of the transition from stable sheet cavity to periodically shedding cloud cavitation using high-speed visualization and time-resolved *X-ray* densitometry measurements in a venture nozzle [40]. Their experimental works