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Pressure oscillation of submerged steam condensation in condensation oscillation regime

Fang Yuan, Daotong Chong [*], Quanbin Zhao, Weixiong Chen, Junjie Yan

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

The condensation oscillation of submerged steam was investigated theoretically and experimentally at the condensation oscillation regime. It was found that pressure oscillation frequency was consistent with the bubble oscillating frequency and there was a quasi-steady stage when bubble diameters remained constant. A thermal-hydraulic model for the condensation oscillation regime was proposed based on potential flow theory, taking into account the effects of interface condensation and translatory flow. Theoretical derivations indicated that oscillation frequencies were mainly determined by bubble diameters and translatory velocity. A force balance model was applied to the calculation of bubble diameters at quasi-steady stage, and the oscillation frequencies were predicted with the calculated diameters. Theoretical analysis and experimental results turned out that oscillation frequencies at the condensation oscillation regime decreased with the increasing steam mass flux and pool temperature. The predicted frequencies corresponded to the experimental data well with the discrepancies of ±21.7%.

1. Introduction

Much attention has been focused on the phenomenon of direct contact condensation (DCC) for the wide application in military industry, nuclear power and some other fields. The mass exchange and momentum transfer enhance the energy transfer across the interface between vapor and water resulting in high efficiency of heat transfer. Particularly, the complicated phenomenon was seen in safety system of advanced nuclear power plant, when the reactor pressure was high, the overpressure steam discharged into the subcooled water pool. Pressure oscillation occurs during the injecting process and does harm to apparatuses in the safety system. Therefore, the pressure oscillation of DCC has drawn much attention in the last few decades.

Pressure oscillation of DCC has been discussed by different investigators. In view of various flow patterns at different steam mass fluxes, the investigations can be classified into high steam mass flux regime and low steam mass flux regime. The condensation regime map is shown in Fig. 1.

The investigations on high steam mass flux are focused on the stable condensation regime. Hong et al. [2] investigated the pressure oscillation in the stable condensation regime, and pointed out that the pressure oscillation was originated by the periodic motion of the steam plume and the dominant frequency was inversely proportional to pool temperature. In addition, he adopted the turbulent jet theory to develop a one-dimensional model which could predict the dominant frequencies well for the steam mass flux between 400 and 900 kg m^{-2} s^{-1}. Qiu et al. proposed a theoretical model on the pressure oscillation amplitude [3] and conducted research on pressure oscillation of sonic steam jet in comparison with supersonic jet [4].

The investigations on low steam mass flux include flow patterns of condensation oscillation, transient chugging and chugging. The oscillation at low steam mass flux was found to be caused by bubble motions; however, the phenomenon in condensation oscillation regime was distinct from chugging, in which the pool water entered the nozzle periodically. The two regimes were studied separately in the previous research due to different thermal hydraulics. Simpson and Chan [5] investigated the pressure oscillations of subsonic steam jets and indicated that the dynamics of subsonic jets was constituted by bubble growth, bubble translation, and bubble detachment. An empirical dimensionless correlation was presented to predict the oscillation frequency based on experimental data. Furthermore, Chan and Lee [6] mainly studied the subsonic steam injection at lower mass fluxes which consisted of chugging and oscillatory bubble. They proposed a condensation regime map with approximate boundaries for various flow patterns and observed that pressure oscillations were characterized by large amplitude

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[*] Corresponding author. Tel.: +86 029 82665359.
E-mail addresses: spiritwalkers@163.com (F. Yuan), dtchong@mail.xjtu.edu.cn (D. Chong), zqb8031110.com@stu.xjtu.edu.cn (Q. Zhao), chenweixiong@mail.xjtu.edu.cn (W. Chen), yanjj@mail.xjtu.edu.cn (J. Yan).

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Nomenclature

c_d	drag coefficient
C_r	rate of condensation (kg m^{-2} s^{-1})
D	bubble diameter (m)
D_h	nozzle diameter (m)
F_{con}	condensation force (N)
F_d	drag force (N)
F_i	inertia force (N)
F_m	steam momentum force (N)
F_p	pressure force (N)
F_s	surface tension force (N)
f	oscillation frequency (s^{-1})
G	steam mass flux (kg m^{-2} s^{-1})
g	gravity (m s^{-2})
h_{fg}	latent heat (J kg^{-1})
h_i	heat transfer coefficient (J m^{-2} K^{-1} s^{-1})
l	distance from the location of the pressure sensor to the axis (m)
p	liquid pressure of external flow (Pa)
p_b	bubble pressure (Pa)
p_s	vapor pressure at nozzle exit (Pa)
p_0	vapor stagnation pressure (Pa)
p_∞	ambient pressure (Pa)
R	bubble radius (m)
R_b	bubble radius at quasi-steady stage (m)
r	distance from bubble center to external liquid (m)
T_s	steam saturation temperature (K)
T_∞	pool water temperature (K)
U	translatory velocity of bubble center (m s^{-1})
v	velocity of external liquid flow (m s^{-1})
V	vapor velocity at the nozzle exit (m s^{-1})
x	dimensionless parameter for oscillation

Greek symbols

β	damping constant (s^{-1})
β_{con}	condensation damping constant (s^{-1})
β_{vis}	viscosity damping constant (s^{-1})
σ	surface tension of water (N m^{-1})
θ	angle between the position vector and the horizontal axis of symmetry
μ	viscosity (N s m^{-2})
γ	adiabatic constant ($\gamma = 1.32$)
ρ	water density (kg m^{-3})
ρ_s	steam density (kg m^{-3})
ω	angular velocity (s^{-1})
ω_0	natural angular velocity (s^{-1})

concurring with bubble detachment and collapse at frequencies lower than 100 Hz. Damasio et al. [7] compared pressure oscillation frequencies with vapor–liquid interface fluctuation frequencies measured by electrical resistive probes, and proposed a dimensionless correlation for frequencies in chugging and condensation oscillation regime. Nariai and Aya [8] classifying the oscillating patterns into detailed regimes including internal chugging, small chugging, bubbling at the steam mass flux less than 200 kg m^{-2} s^{-1}, and developed a theoretical bubble model for oscillation frequency at low steam mass flux on the basis of the original Rayleigh equation with a modified continuity equation. Youn et al. [9] discussed the dynamic oscillation of high pressure pulses with low frequency in the chugging region experimentally and observed that a negative pressure was originated by sudden condensation after bubble collapse. Li et al. [10] simulated the flow phenomenon at low mass flux by using the VOF model and LES turbulence model, four typical stages—the initial stage, the maximum stability stage, the oscillatory stage and the detachment stage—observed in the simulation were consistent with the experimental results of Chan and Lee [6], however, the calculated frequency didn't match well with the experimental frequency.

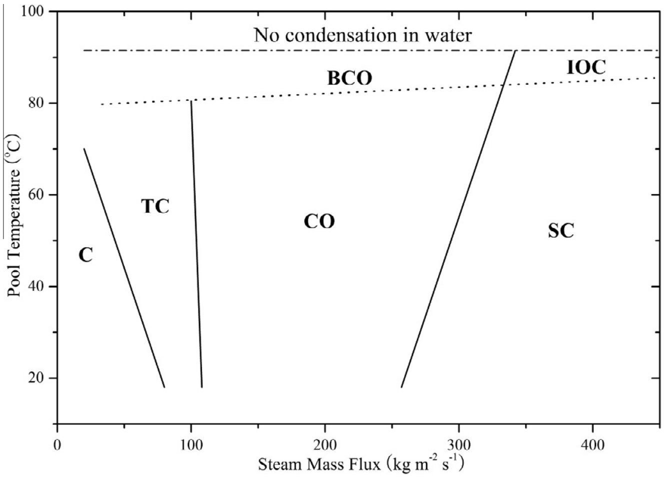

Fig. 1. Condensation regime map by Cho et al. [1] (C–chugging, TC—transitional region from chugging to CO, CO—condensation oscillation, SC—stable condensation, BCO—bubble condensation oscillation, IOC—interfacial oscillation condensation).

In view of the above research, the condensation oscillation was influenced by the periodic bubble motions. Regarding the bubble dynamics, much work has been devoted to it theoretically. A great number of modifications have been performed on the basic equation to apply to different conditions. Several theoretical models were proposed in the research on the bubble motions at a submerged nozzle or orifice, among which the force balance theory, the Rayleigh equation and the potential flow theory were the most popular. Some analytical studies done by various authors are summarized in Table 1.

Many investigations based on the force balance theory were analyzed with empirical detachment distance of neck [11–14]. Due to the lack of empirical research, the force balance theory was not applicable for the dynamic analysis of vapor bubble motions. Moreover, the generalized Rayleigh equation in [15] was derived from continuity equation which neglected the condensation effect. Therefore, the Rayleigh equation should be modified to apply to the flow conditions in condensation oscillation.

Above all, the pressure oscillation at the condensation oscillation regime was mainly experimentally studied, but there were no abundant photographic results and the mechanism related to the bubble dynamics was still to be revealed. In this paper, we conducted an experimental and theoretical investigation on the pressure oscillation at the condensation oscillation regime. Periodic motions of vapor bubbles and pressure oscillation were recorded in the experiment. A thermal-hydraulic model based on potential flow theory was proposed to describe the bubble oscillation in the regime, taking into account the effects of interface condensation and translatory flow. A force balance model including the condensation effect was introduced to predict the diameter at the quasi-steady stage. Consequently, the oscillation frequencies at different thermal hydraulic conditions were predicted with the