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Research Paper

Condensation regime diagram for supersonic and subsonic steam jet condensation in water flow in a vertical pipe

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HIGHLIGHTS

- Supersonic and subsonic steam jet condensation in water flow is studied visually.
- Strong correlation between condensation regimes and pressure oscillation is found.
- Scaled steam mass flux is irrelevant to the transitional lines in the regime diagram.
- Condensation regime diagram is developed to describe the four condensation regimes.
- Condensation regime diagram at low ambient pressure can be applied to high pressure.

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ABSTRACT

An experimental research is performed to investigate the condensation regime diagram of supersonic and subsonic steam jet condensation in water flow in pipes. The original images of the jet plume are recorded using a visualization window and a high-speed camera. The jet condensation regimes are basically categorized into four types, including Chugging, Oscil-I, Oscil-II and Stable regimes, primarily based on the transient evolution of geometrical profile of the jet plume. And the average geometrical shape of the jet plume is found to shrink gradually with increase of ambient pressure. The stand deviation of pressure oscillation is highly correlated to jet condensation regimes, so it can be applied to quantitatively categorize different regimes. The steam mass flux, scaled by critical steam mass flux at different ambient pressure, is found to be irrelevant to the transitional lines among Chugging, Oscil-I, and "Stable or Oscil-II" regimes in the condensation regime diagram. Furthermore, the Oscil-II regime can be simply isolated from the "Stable or Oscil-II" regime via comparison of the standard deviation of pressure oscillation in this two regimes. Therefore, the jet condensation regime diagram obtained from low ambient pressure could be applied to conditions of elevated ambient pressure.

1. Introduction

Direct contact condensation is an effective heat and mass transfer mechanism, commonly used in a wide variety of applications such as liquid propellant rocket engines, water-cooled nuclear reactors, and solar refrigeration systems [1–3]. However, its application is limited by the occurrence of undesired condensation regimes along with intense fluid pressure oscillation. In order to improve the thermal efficiency of the rocket engines, a small amount of gas oxygen is discharged into a liquid oxygen flow in pipes [1,4]. The process of vapor jet condensation results in transient characteristics including multiscale interfaces and highly turbulent flows. The evolution of gas-liquid interfaces under various conditions forms many categories of different condensation regimes. Some condensation regimes occur along with substantial pressure fluctuation, ultimately rendering the rocket vehicle susceptible to longitudinal vibration. Therefore, in view of flow assurance, much attention should be paid to identify condensation regimes of vapor jet in liquid pipeline systems.

Considerable research has been performed on the subject of interface regimes of a gas jet in liquid. In terms of non-condensing gas jet in liquid, two regimes including both bubbling regime and jetting regime were found experimentally by Weiland and Vlachos [5,6]. For gas jet condensation in liquid, Chan and Lee [7] were the pioneers to figure out a condensation regime diagram at very low steam mass flux ($1 < G_s < 175\ \mathrm{kg/m^2\ s}$). By analyzing the high-speed videos, the interface behaviors of the steam-water were systematically categorized into six different condensation regimes with two variables of both steam mass flux and pool

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Nomenclature

A_{throat}	cross-section area of the nozzle throat, m^2
A_{exit}	cross-section area of the nozzle exit, m^2
d_e	inner diameter of the convergent-divergent nozzle exit, m
d_{in}	inner diameter of the convergent-divergent nozzle inlet, m
d_{th}	inner diameter of the convergent-divergent nozzle throat, m
d_m	maximum diameter of the steam plume, m
D	inner diameter of the vertical round pipe, m
G_s	steam mass flux at the nozzle exit, kg/m^2 s
$G_{c,\ exit}$	critical steam mass flux at ambient pressure, kg/m^2 s
$G_{c,\ throat}$	equivalent critical steam mass flux, kg/m^2 s
i	ordinal of data points in a test sample, 1
M	data points in a test sample, 1
m_w	water flow rate, kg/s
N	scaled steam mass flux, 1
$\bar{p}$	mean of pressure, kPa
p_{sd}	stand deviation of pressure, kPa

p_i	signal of pressure oscillation, kPa
p_s	steam inlet pressure, MPa
p_w	water pressure at the steam injection point, MPa
PDF	Probability Density Function, 1
PSD	Power Spectrum Density, 1^2/Hz
Re_w	Reynolds number of water flow equals to $4m_w/\pi D\mu_w$, 1
t	time, s
T_s	steam inlet temperature, °C
T_w	water inlet temperature, °C
V_c	local sonic velocity of steam, m/s

Greek letters

θ	angle between the nozzle center line and the pipe wall, °
μ_w	dynamic viscosity of water, N s/m^2
ρ_c	density of steam jet at local sonic velocity, kg/m^3

Subscripts

s	the steam phase
w	the water phase

temperature. As for a relatively wide range of steam mass flux up to 700 kg/m^2 s, Chun et al. [8] found that there were six different types of condensation regimes, i.e., chugging, condensation oscillation, transitional region from chugging to condensation oscillation, bubbling condensation oscillation, interfacial oscillation condensation, and stable condensation. With et al. [9] suggested that the nozzle diameter also had significant influence on the condensation regimes, which were then divided into seven different regimes, including chugging, bubbling, conical jetting, ellipsoidal jetting, divergent jetting, interfacial condensation oscillation, and no condensation. In case of a steam jet discharging from a convergent-divergent nozzle into a subcooled water pool, Wu et al. [10] found visually that six condensation regimes appeared, including contraction, expansion-contraction, double expansion-contraction, contraction-expansion-contraction, contraction-expansion-divergent, and divergent shape. When a steam jet is discharged from an equal-diameter nozzle into a water flow in pipes, Xu et al. [4,11] found that there were mainly four different condensation regimes, i.e., Chugging, Oscillation-I, Oscillation-II and Stable condensation regimes. However, until now there are still no published report focusing on condensation regimes of steam jet discharging from a convergent-divergent into a water flow in pipes.

Noticeably, the methodologies of categorizing condensation regimes reviewed above are dominantly relied on either experimental visualization or semi-empirical thermal dynamical model, leading to classifications of condensation regimes from different researchers neither objective nor quantitative. Even worse, in the transition regions of condensation regimes, significant contrasts from different observers inevitably occurs. Fortunately, as flow signals contain plentiful information of multiphase flow, the flow signals have been proved to possess great potential in recognition of flow regimes [12,13]. Some other effective approaches have been proposed to more objectively categorize flow regimes with extraction of characteristic variables from the signal of the gas-liquid two-phase flow, such as fluctuations of pressure and void fraction, which are assumed to reveal the flow configuration [14,15]. Statistical moment, probability density function, and power spectral density function of the signals are typically satisfactory indicators of flow regimes, and then much less parameters extracted from these time and frequency parameters could be applied to allow for clustering features of flow regimes [16–18]. For condensing jet in stagnant water tank, it was found that the positive correlation between the dominant frequency of pressure oscillation and steam mass flux translated to negative correlation, when the stable condensation regime changed to condensation unstable regimes [19–23].

Additionally, a large amount of research about steam jet condensation in water are on the subjects of heat transfer coefficient, jet penetration length, and turbulent jet flow field. Heat transfer across the gas-liquid interface were usually described through interfacial transportation theory, and also many semi-empirical correlations were recommended to approximate heat transfer coefficient [8–11]. Kerney et al. [24] derived the initial semi-empirical correlation of the jet penetration length with dependencies of dimensionless steam mass flux and condensation driving potential. Based on Kerney et al.'s semi-empirical correlation, and then a variety of different correlations were proposed in respect to different test conditions [25,26]. The turbulent jet flow fields were typically visualized via Particle Image Velocity, Planar Laser Induced Fluorescence [27–31], and it was found that the profiles of axial velocity and temperature of the turbulent condensing jet follow self-similarity well. The turbulent jet instabilities were found to be generated at the steam water interface, which yields pressure stresses in a non-deterministic way [32,33].

The purpose of this work is to investigate the classification of condensation regimes of supersonic and subsonic steam jet discharging from a convergent-divergent nozzle into a water flow in pipes based on the statistical features of pressure oscillation. A visualized vertical round pipe with a convergent-divergent nozzle was fabricated. The jet condensation regimes were visualized via a high-speed video camera, and the pressure oscillations in the pipe flow were measured through high-frequency pressure transducers. The standard deviation of pressure oscillation signal was utilized to distinguish various jet condensation regimes. The results are expected to allow for further exploration on the condensation regime mechanisms of steam jet condensation in water flow in pipes.

2. Experimental apparatus

Experiments of steam/water two-phase flow were conducted on the test loop illustrated in Fig. 1. The test loop is organized in four major parts, including a steam supply line, a water supply line,