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Numerical modeling of flow film boiling in cryogenic chilldown process using the AIAD framework

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ABSTRACT

Flow film boiling plays a dominant role in cryogenic chilldown process, which involves complicated heat transfer and flow regime transition. Nevertheless, existing researches about flow film boiling with cryogenic fluids are relatively limited. In this study, a Computational Fluid Dynamics (CFD) model based on a wall heat flux partition algorithm is built. The AIAD framework implemented in the two-fluid model is employed to appropriately calculate the drag force on the liquid-vapor interfaces. The CFD model is validated by the satisfactory coincidence between the simulated heat fluxes and experimental data in literature. Accordingly, the two-phase interaction on the flow regime and heat transfer is further investigated. The results reveal that the vapor film beneath the bulk liquid becomes thinner due to the drag force on the liquid-vapor interface. In addition, FFT analysis on the pressure drop shows that dominant frequency of the interfacial waves in the tube mainly locates around 2.8 Hz. The normalized intensity indicates that fluctuation becomes more violent with the increase of superheat and inlet liquid flow rate. Finally, comparison between correlations and experimental data indicates that a correlation of heat transfer coefficient considering both film boiling effect and forced convective flow effect needs to be proposed.

1. Introduction

Cryogenic fluids, including liquid nitrogen (LN2), liquid oxygen (LO2), liquid hydrogen (LH2), liquefied natural gas (LNG), are involved in the propulsion and thermal management for space missions, medical applications and industrial process, etc. Generally cryogenic fluids are conveyed by piping systems at adiabatic environment. Before conveying, piping systems need initially to be chilled down from the ambient temperature to saturation temperature of the working fluids to ensure the transport process free of vapor. An intense evaporation of the cryogen is expected to occur inevitably during the chilldown process. In order to avoid an excessive loss of cryogen and dangerous pressure fluctuations in the pipeline, a basic understanding of the chilldown process is needed.

1.1. Cryogenic chilldown

Cryogenic fluids own some particular thermal properties compared with room-temperature fluids like water (e.g. small surface tension, small latent heat, near zero wetting angle and large ratio of vapor density to liquid density) [1,2], which results in different behaviors of heat transfer and flow regimes. Studies on cryogenic chilldown started in the 1960′s accompanying with the fast growing rocket launching systems [3]. Previous researchers focused on obtaining heat transfer charateristics and chilldown time. Following researches [4–7] found chilldown process undergoes various flow regimes that differ with channel orientation (e.g. horizontal, vertical), mass flux, inlet cooling and fluid properties, etc. It is also noted that definitions of the flow regimes are somewhat arbitrary since qualitative assessment has not been done yet, and transition criteria between different flow regimes are not fully understood.

Different flow regimes are often associated with different heat transfer mechanisms. Generally, cryogenic chilldown process successively experiences single-phase vapor convection, film boiling, transient boiling, nucleate boiling and single-phase liquid convection. When phase change occurs as two-phase mixture flows along the channel in chilldown process, the situation is even more complicated: different flow regimes are generally observed at different positions along the channel. As a result, heat transfer characteristics in chilldown process are still poorly understood due to the intricate interaction between the two-phase flow and boiling heat transfer.

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Nomenclature

A	interfacial area density, m^2/m^3
A_b	area proportion covered by nucleating bubbles
C_D	drag coefficient
D	tube inner diameter, m
d_B	bubble diameter, m
d_D	droplet diameter, m
F_D	interfacial shear stress, N/m^3
f	bubble departure frequency, Hz
h	heat transfer coefficient, $W/m^2{\cdot}K$
h_{lv}	latent heat of evaporation, J/kg
k	thermal conductivity, W/m·K
L	tube length, m
m	mass flow rate, kg/m^2 s
q_c	convective heat flux, W/m^2
q_e	evaporative heat flux, W/m^2
q_q	quenching heat flux, W/m^2
q_w	total heat flux from the wall, W/m^2
Re_{in}	Reynolds number of inlet liquid
T	temperature, K
t	time, s

Greek letters

α	volume fraction
ρ	density, kg/m^3
ρ_{lv}	average density, kg/m^3
μ	viscosity, Pa·s
ΔT	wall superheat, K

Subscripts

B	bubble
D	droplet
FS	free surface
G	gas
i	interface
l	liquid
w	wall
v	vapor

Abbreviations

AIAD	Algebraic Interfacial Area Density
LN2	liquid nitrogen

1.2. Flow film boiling

Film boiling plays a dominant role in the chilldown process since it lasts the longest time due to large wall superheats. Therefore, a comprehensive understanding of flow regime and heat transfer characteristics for flow film boiling is in urgent need. Existing film boiling researches for heat transfer with cryogenic fluids, however, are relatively limited, because (1) historically, film boiling has not been a central concern in industrial applications; and (2) large wall superheat in cryogenic system leads to numerous experimental challenges such as large material expansions, incompatibility of materials, excessive heat loss, dangerous operating conditions, among others.

During flow film boiling in a horizontal tube, liquid is surrounded by the vapor generated from wall boiling, forming a stratified flow structure, as shown in Fig. 1. The upper space is occupied by the bulk vapor, and liquid is supported on a lighter vapor film in the lower space. When liquid and vapor travel at different horizontal velocities, interfacial waves occurring on the liquid-vapor interfaces according to Kelvin-Helmholtz (KH) instability [8]. In the KH theory, the interfacial drag force, which is proportional to the relative velocity between liquid and vapor, causes the interfacial waves. The interaction between liquid and vapor will further influence the boiling process and bubble motion.

Though several experiments on the whole chilldown process, including flow film boiling, have been conducted, the attention mainly focuses on obtaining heat transfer correlations. These correlations fail to consider local variations of heat transfer associated with the two-phase flow structure. In reality, for the same vapor quality, the local heat transfer rate for annular flow is significantly different from that for stratified flow.

Liao [9] observed liquid filaments in film boiling region under low flow rates. Laverty and Rohsenow [10] experimentally observed the annular flow regime exists in a uniformly heated tube with LN2 flowing upward through. They also concluded that it is difficult to obtain a simple expression by experiments for heat transfer coefficient due to the large amount of vapor superheat.

1.3. CFD models for stratified flow

CFD modeling has been widely used in boiling phenomenon recently due to its advantages in providing more insight into the physics of gas-liquid flow [11–13]. Welch and Rachidi [14] built a two-dimensional model for pool film boiling including conjugate

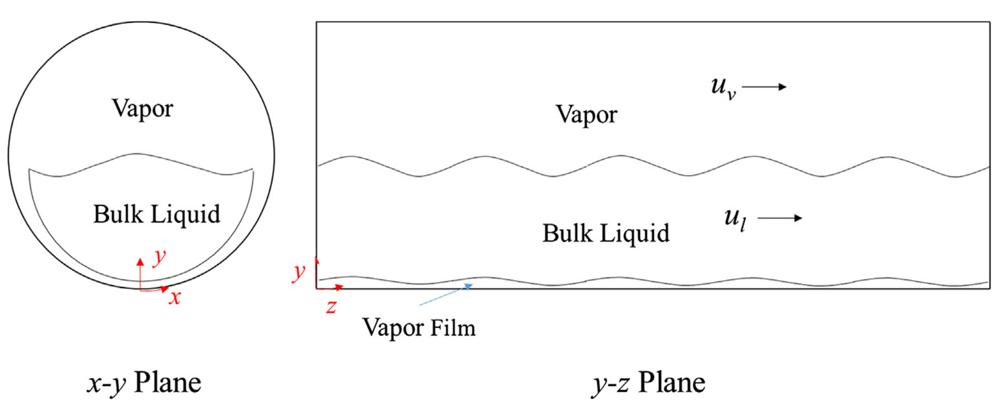

Fig. 1. Schematic of flow regime of flow boiling film.