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Research Paper

Flow boiling instability of liquid nitrogen in horizontal mini channels

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HIGHLIGHTS

- The proposed model couples the LN_2 flow boiling with the liquid supply.
- The model is validated relative to the experimental results.
- Ledinegg instability, pressure drop and density wave oscillation are studied.
- The dynamic response of LN_2 instabilities are compared with other fluids.

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ABSTRACT

In the study, flow boiling instability in horizontal mini-channels is investigated by developing a numerical model that couples flow boiling with the flow supply of liquid nitrogen. The model is validated relative to the experimental results. The results indicate that the heat flux and inlet subcooling significantly influence steady-state characteristic curves. Transient responses of Ledinegg instability, density wave, and pressure drop oscillations are investigated, and comparisons with room-temperature fluids are presented. With respect to the Ledinegg instability, the flow is stabilized away from the site where a positive flow disturbance occurs at the two-phase negative slope region, and the flow exhibits periodic oscillations initially when the negative disturbance is applied. With respect to the conditions of the density wave and pressure drop oscillations, the flow exhibits periodic oscillations when disturbance occurs. The characteristics of the three types of instability of liquid nitrogen flow boiling are compared with those of water/refrigerant fluids.

1. Introduction

The heat transfer coefficient of two-phase flow boiling is high due to the simultaneous use of the sensible heat and latent heat of the fluid. It is an ideal technique to achieve high heat flux and uniform temperature distribution in heat transfer. Several studies focused on heat transfer through flow boiling in mini channels due to advantages including high heat transfer coefficient, high operating pressure, low mass flux, and compact channel size. Therefore, it is widely used in applications such as electronic equipment cooling, equipment cooling under microgravity conditions, and heat exchangers in hydrogen energy storage systems [1]. Liquid nitrogen is colorless, odorless, non-combustible, non-flammable, and plentiful, and it constitutes an ideal cooling fluid in the low temperature region. Liquid nitrogen is currently widely used in several fields [2] including aerospace, energy industry, high temperature superconductivity, and low temperature biological medicine. The investigation of the flow boiling characteristics of liquid nitrogen in mini channels is extremely important for the development of highly-efficient and compact cryogenic heat exchangers and also enriches our understanding of the heat transfer characteristics of the flow boiling in low temperature regions. The studies on flow boiling in mini channels mainly focused on the heat transfer coefficient, pressure drop, and flow instability. However, the understanding of the characteristics of flow instability still remains elusive.

Unstable flows are easily induced due to the mismatch between the flow supply and demand of mass flux. When an unstable flow is generated, it results in periodic oscillations of mass flux and pressure in the channel that can lead to mechanical vibration, noise, and control problems in the system. Unstable flow can also worsen the flow boiling heat transfer performance and lead to wall temperature fluctuations and exacerbate material thermal fatigue. Furthermore, it can result in the failure of the cooling effect and emergence of dry out phenomena, thereby threatening the safe operation of the system. Therefore, the study on flow boiling instability in channels is crucial to improve the

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Nomenclature

G	mass flux, $kg\,m^{-2}\,s^{-1}$
m	gas mass, kg
u	fluid velocity, $m\,s^{-1}$
V	volume, m^3
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
x	vapor quality
Re	Reynolds number
T	temperature, K
H_{LV}	latent heat of vaporization, $J\,kg^{-1}$
H	enthalpy, $J\,kg^{-1}$
R_g	gas constant of nitrogen, $J\,kg^{-1}\,K^{-1}$
D_{in}	inner diameter, mm
A_c	actual internal area, m^2
p	pressure, kPa
q	heat flux, $kW\,m^{-2}$
Δp_{tot}	overall pressure drop, kPa
Δp	pressure drop, kPa
L_q	heating length, mm
z	tube position, m
Bo	boiling number
We	Weber number
ΔT_{sub}	degree of supercooling, K
$C_{p,L}$	specific heat, J/(kg·K)
Dh	equivalent diameter, mm
Bd	Bond number
g	acceleration of gravity, m/s^2
$h(z)$	heat transfer coefficient, $W/(m^2 \cdot K)$

Greek symbols

ρ	density, $kg\,m^3$
ξ_h	heated perimeter, m
λ	thermal conductivity, W/m K
f	frictional coefficient
σ	surface tension, N/m

Subscripts

m	average of vapor and liquid
L	liquid
V	gas
LO	all liquid
W	wall
min	minimum
sub	subcooled
$inlet$	inlet of the tube
$outlet$	outlet of the tube
sat	saturation condition
in	inner wall
f	fluid

heat transfer performance and also ensure system security.

A summary of previous studies on two-phase flow oscillations in horizontal and vertical channels are listed in Table 1. Most studies (Kakaç [3], Kakaç and Cao [4], Padki et al. [5], Cao et al. [6], Hetsroni et al. [7], Qu and Mudawar [14], Zhang et al. [16], Ding et al. [17], Çomaklı et al. [24], Fukuda et al. [28]) focused on dynamic oscillations, including pressure drop oscillation, density wave oscillation, and thermal oscillation. The oscillations depend on parameters including heat flux, mass flux, and inlet subcooling. A few studies focused on static instabilities such as the Ledinegg instability (Ruspini et al. [34]).

Some uncommon oscillations were also determined in previous studies. Wu and Cheng [8] observed large-amplitude/long-period boiling fluctuations in microsystems for the first time, and the fluctuation periods were dependent on the channel size, heat flux, and mass flux. Xu et al. [15] observed instabilities showing large amplitude/long period oscillations superimposed with small amplitude/short period oscillations. They also determined the thermal oscillations that accompany both the aforementioned oscillations. Three types of unstable boiling modes were also observed by Wu and Cheng [9], and the liquid/two-phase/vapor alternating flow exhibited the largest oscillation amplitudes. Brutin et al. [26] observed two types of behavior, namely one with low amplitudes and no characteristic frequency, and the other is in a non-stationary state. Wang et al. [27] investigated long-period oscillation (more than 1 s) and short-period oscillation, and they combined oscillations with the flow pattern via a simultaneous visualization and measurement study. The onset of instability was examined in several studies (Wang et al. [18], Kennedy et al. [19], Stoddard et al. [23]) to understand the initial condition of the flow instabilities.

Previous studies on the flow boiling instability of liquid nitrogen mainly focused on oscillations at the onset of nucleate boiling (ONB) in a vertical channel (Qi et al. [28]). They observed stable long period (50–60 s) and large-amplitude oscillations of mass flux, pressure drop, and temperature and termed this as ONB oscillation. The stable and unstable regions were classified. Fukuda et al. [29] obtained two unstable regions in a vertical heat exchanger, namely one under a low flow rate and one under a high flow rate.

It was observed that the aforementioned studies primarily focused on the flow boiling instability of room-temperature fluids and refrigerants in channels. There is a paucity of studies on flow boiling using cryogenic fluids although they are essential to resolve heat transfer problems in low temperature regions. For example, a compact heat exchangers with liquid nitrogen as the working fluid are indispensable to address the heat dissipation problem of small equipment at cryogenic temperatures. However, thermophysical properties of cryogenic fluids differ considerably from those of room-temperature fluids. Thus, the conclusions obtained from room-temperature fluids cannot be used directly, and further studies should be performed, especially with respect to cryogenic fluids. In the present study, we develop a numerical model to investigate the flow instability of liquid nitrogen in mini horizontal channels under various operating conditions, particularly in situations which cannot be replicated in experiments. We also compare the results from the numerical simulation with experimental results to enrich our understanding of two-phase flow characteristics.

Previous studies developed an experimental apparatus to investigate the flow boiling of liquid nitrogen in horizontal mini-tubes and performed extensive experiments on the characteristics of the heat transfer coefficient [30], friction factor [31], and critical heat flux [32]. In this study, we develop a transient numerical model that couples the flow boiling and system flow of liquid nitrogen to predict the flow boiling instability characteristics in horizontal mini channels. The dynamic response of three types of oscillations, namely density wave oscillation, pressure drop oscillation, and Ledinegg instability, are analyzed. We demonstrate the regions of the steady state characteristic curve for the three types of oscillations to occur and reveal the dependences of the flow instabilities on parameters related to the mass flux, heat flux, and inlet subcooling. The study improves the understanding of the instabilities that occur in flow boiling by employing a cryogenic liquid and can aid in enhancing the stability and operational safety of systems.

2. Numerical model

In the present study, we focus on the flow boiling instability that is caused by the mismatch between the flow supply and the flow boiling in the horizontal mini-tubes (test section). For example, when the mass