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Experimental investigation of saturated flow boiling heat transfer of nitrogen in a macro-tube

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ABSTRACT

The saturated flow boiling heat transfer of nitrogen (N_2) in a vertical upward 11.9 mm inner diameter stainless steel tube was experimentally investigated. The heat transfer coefficient (HTC) was measured as a function of vapor quality. Totally 414 experimental data points were obtained, with the parameter range of vapor quality from 0.01 to 0.99, pressure from 0.84 to 2.29 MPa, heat flux from 9 to 98.8 kW/m^2, and mass flux from 110 to 800 kg/m^2 s. The effects of vapor quality, heat flux, mass flux, and pressure on the HTC are explored. Four flow patterns are identified by analyzing the HTC data, including bubbly flow, annular flow with liquid in the core and vapor between the liquid and the tube wall, dispersed flow, and mist flow. The trend of the HTC along the tube length (with vapor quality) is explained in relation to flow patterns. The flow and heat transfer characteristics in the experiments are compared with those in horizontal macro-tubes. Substantial differences between these two flow directions are revealed. For upward flow in vertical macro-tubes, it is fairly commonly seen that there are two occurrences of critical heat flux (CHF) along a uniformly heated channel. The mechanisms resulting in this phenomenon are found. The experimental data are compared with the correlations of saturated flow boiling heat transfer coefficient. The best one has a mean absolute deviation of 16.6%.

1. Introduction

Nitrogen (N_2) is an important cryogenic coolant in many fields, such as high temperature superconductors, high power electronic elements, cryogenic surgical apparatus, cryoresistive cables, air separation systems, and aerospace systems. In the design and application of these cryogenic cooling systems, the determination of N_2 flow boiling heat transfer in channels is required.

The most important characteristics of N_2 are low surface tension, low latent heat of vaporization, and small liquid-surface contact angle, which are much different from conventional fluids. Many researchers [1–3] suggested that as a cryogenic fluid N_2 flow boiling heat transfer and flow characteristics were quite different from conventional fluids.

Due to the extremely high costs on experimental facilities and its complexity of measurements, the experimental investigations of N_2 flow boiling heat transfer were limited, leading to insufficient understanding of N_2 heat transfer mechanisms and characteristics, as can be seen from the following literature review.

Laverty and Rohsenow [4] were among the earliest researchers investigating N_2 flow boiling heat transfer in tubes. They conducted a visual study of boiling heat transfer of N_2 flowing vertically upward in a uniformly heated tube of 8.1 mm inner diameter (ID), with mass flux from 95 to 285 kg/m^{2}s, heat flux from 11 to 95 kW/m^2, superheat from 111 to 542 °C, heat transfer coefficient (HTC) from 63 to 372 W/m^2 K, inlet quality of zero, and pressure about 120 kPa. It was observed that the annular flow, which has liquid in the core and vapor between the liquid and the tube wall, might exist at very low vapor qualities around 0.05, and the annular vapor film was broken up at higher vapor qualities to form a dispersed flow of droplets and filaments of liquid carried along in a vapor matrix. The dispersed flow featured the decrease of average liquid drop size with increasing length (and vapor quality) and a tendency of the largest liquid particles to be concentrated in the vapor boundary layer. Also noticeable was the characteristic for the particles to become more uniformly distributed at greater vapor qualities. For mass flux greater than 270 kg/m^2 s and heat flux greater than 43 kW/m^2, the HTC along the axial direction had two peaks and one valley, with the first peak and the valley occurring at very low vapor quality and the first peak much higher than the second. No explanation was provided for the mechanism of this phenomenon.

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Nomenclature

A_c	flow area of the test section (m^2)
c_p	constant-pressure specific heat (J/kg K)
D	inner diameter (m)
D_o	outer diameter (m)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K); enthalpy (J/kg)
h_{lg}	latent heat of vaporization (J/kg)
L	channel length (m)
ΔL	distance between two adjacent thermocouples on tube wall
Pr	Prandtl number
p	pressure (Pa)
Q	heating power (W)
q	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
V	volumetric flow rate (m^3/s)
x	thermodynamic equilibrium quality

Greek symbols

λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)

Subscripts

in	inlet
j	number of cross section
l	liquid
lo	liquid only, i.e. assuming all fluids are liquid
out	outlet
sat	saturated
sp	single-phase
wi	inner surface of tube wall
wo	outer surface of tube wall

Klimenko and Sudarchikov [1] conducted an experimental study of N_2 flow boiling heat transfer in a vertically upward 10 mm ID stainless steel tube, with mass flux from 170 to 750 kg/m^2 s, heat flux from 10.2 to 42.7 kW/m^2, and inlet pressure from 180 to 700 kPa. The results showed that the HTC increased with increasing heat flux and vapor quality at low vapor quality and grew slightly with increasing pressure. Both nucleate boiling dominant region and two-phase forced convection dominant region were observed. They defined a modified boiling number to distinguish the two regions.

The Zhang group [3,5–7] investigated experimentally the N_2 flow boiling heat transfer in vertically upward small tubes with 0.531, 0.834, 1.042, and 1.931 mm IDs, with the flow patterns visualized using a high-speed digital camera. The parameter range was mass flux from 450 to 1700 kg/m^2 s, heat flux from 181 to 135 kW/m^2, pressure from 180 to 730 kPa, and vapor quality from 0.01 to 0.89. Four typical flow patterns, including bubbly, slug, churn and annular flows, were observed, with annular flow covering most regions and yielding the best heat transfer performance and bubbly flow and slug flow only occupying narrow range ($x < 0.15$). The annular flow had a vapor core with liquid film between the tube wall and the vapor core, which was completely different from the annular flow observed by Laverty and Rohsenow [4]. Dryout easily happened in the 0.531 mm ID tube, which led to high vapor quality and finally mist flow appeared. For the 0.531 mm ID tube, when mass flux increased from 677.4 to 1006.3 kg/m^2 s and inlet pressure from 209.2 to 478.6 kPa, the maximum HTC was almost doubled from 5.3 to 10.3 kW/m^2 K, and the vapor quality for the transition of annular flow to mist flow was greatly increased from 0.4 to 0.7. The flow regime transition lines of slug/churn flow and churn/annular flow moved to lower superficial vapor velocity, while that of bubbly/slug flow moved to higher superficial vapor velocity compared to the results for the room-temperature fluids such as air–water and refrigerants. The surface tension force and the drop diameter size were revealed to be the major factors affecting the flow pattern transitions of N_2 two-phase flow boiling. Two-phase flow instability like periodical oscillations was frequently detected at high-mass flux. The heat transfer characteristics of 1.931 mm tube were quite different from the three smaller ones, being similar to those of macro-channels under the experimental conditions. For the 1.931 mm tube, at the given mass flux, heat flux and inlet condition, the HTC along the axial direction had two peaks and one valley, with the first peak lower than the second [7]. Besides, this trend did not appear in the 0.531, 0.834, and 1.042 mm ID tubes. The mechanism of this phenomenon was not explained.

Umekawa et al. [8] conducted an experimental study of boiling heat transfer of N_2 natural convection upward in two vertical stainless steel tubes with 3 mm and 5 mm IDs. The experimental parameter range was mass flux from 40 to 250 kg/m^2 s, heat flux from 1 to 34 kW/m^2, pressure from 300 to 400 kPa, inlet subcooling from 0.2 to 11.1 K, and vapor quality up to 1.0. The results showed that the HTC was weak function of the flow oscillations in the boiling channel, and that the HTC in the saturated boiling and post-dryout regions could be predicted by correlations developed for normal fluids under steady flow conditions. Later, Umekawa et al. [9] experimentally studied the N_2 flow boiling heat transfer in a vertically downward 5 mm ID stainless steel tube, with mass flux from 147 to 465 kg/m^2 s, heat flux from 2 to 21.5 kW/m^2, vapor quality less than 0.22, and outlet open to the atmosphere at pressure 100 kPa. The heat transfer was nucleate boiling dominant, almost independent of vapor quality.

Li et al. [10] experimentally investigated the instability of N_2 flow boiling in a vertically upward 6 mm ID stainless steel tube, with heat flux from 0.89 to 13.5 kW/m^2 and pressure from 180 to 1460 kPa. The results showed that with the constant pressure the mass flux decreased with increasing heat flux and vice versa. The mass flux in a steady stage fluctuated around a certain constant value, fluctuating stronger under lower mass flux and being suppressed gradually with increasing pressure.

Yu [11] experimentally studied the N_2 upward flow boiling heat transfer in a vertical 14 mm ID stainless steel tube, with mass flux from 28 to 111 kg/m^2 s, heat flux from 4.2 to 33 kW/m^2, inlet temperature from 90.7 to 104.7 K, and inlet pressures of 0.6 and 1.0 MPa. The phenomenon that along the axial direction the HTC had two peaks and one valley, forming a V-shape, was frequently observed. It was explained that between the first peak and the valley, i.e. the left side of the V-shape, nucleate boiling dominated, and the nucleate boiling became weak with increasing vapor quality because the liquid film became thinner, causing the decrease of the HTC. After the valley two-phase forced convection became important, which made the HTC increase, and the HTC decreasing after the second peak was because a vapor layer appeared between the tube wall and the liquid.

The above reviewed articles on experimental investigations of N_2 flow boiling heat transfer in vertical channels are in the