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Experimental investigation of forced flow boiling of nitrogen in a horizontal corrugated stainless steel tube

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ABSTRACT

Experimental investigation is performed on the heat transfer characteristics of forced flow boiling of saturated liquid nitrogen (LN_2) in a horizontal corrugated stainless steel tube with a 17.6 mm maximum inner diameter. The local heat transfer coefficients (HTCs) are measured at two mass flow rates with a wide range of wall heat fluxes. The effects of the heat flux, mass flow flux and vapor quality on the two-phase heat transfer characteristics are discussed. The results reveal that the local HTCs increase with the heat flux and mass flow flux. The measured local HTCs present a strong dependence on the heat flux. The circumferential averages of the HTCs for the present corrugated tube are compared with the empirical correlations proposed for the smooth tubes, and the results show that the heat transfer is enhanced due to the area augmentation.

1. Introduction

Flow boiling has received great attention from many researchers due to its excellent heat transfer performance, and the related characteristics of different working fluids have been extensively studied. So far most researches on the two-phase flow boiling focus on the ordinary fluids, such as water and refrigerants, while there are relatively fewer experimental works on the cryogenic fluids owing to the comparative difficulties and high expenses. As a result, the empirical correlations derived from the ordinary fluids are usually employed for the predictions of the heat transfer characteristics of the cryogenic fluids. However, it has been pointed out by Klimenko [1] that several popular correlations of ordinary fluids perform badly on Steiner's experimental data of two-phase flow boiling of LN_2 [2]. Much more detailed research of flow boiling focusing on cryogenic fluids is badly in need at present due to the increasing requirements from industries.

Liquid nitrogen is one of the most commonly used cryogenic fluids both in academic research and engineering applications for its representative thermo-physical characteristics. It is also safe and low-cost which makes it popular in a lot of experimental studies. Considering these reasons, liquid nitrogen is chosen as the test fluid for the present experimental research. A wide range study of two-phase flow boiling was reported in public literatures, covering different geometries of regular, mini/micro-channels in terrestrial and reduced gravity. Literature review followed is conducted focusing on LN_2 flow boiling in regular-size tubes under normal gravity. The investigations of flow boiling of cryogenic fluids started in the 1960s, and earlier surveys of the experimental data before 1970s were conducted in Refs. [3,4]. The experimental data and various boiling theories in early years provide us with comprehensive understandings of the basic flow boiling phenomena. The two-phase heat transfer is affected by the mass flow flux, heat flux, vapor quality, tube diameter and the corresponding flow regimes. Steiner [2] studied the forced flow boiling of LN_2 in a smooth horizontal copper tube, and found that the heat flux plays the most important role in the nucleate boiling region of the two-phase heat transfer. Besides, the mass flow flux and vapor quality also affects the two-phase heat transfer. Klimenko et al. [5,6] did experimental research on the subcooled forced flow boiling of LN_2 in vertical and horizontal tubes with different inner diameters. The results showed that the Froude number, which reflects the integrated effects of the tube diameter and flow velocity, affects the two-phase heat transfer for vertical flow and non-stratified horizontal flow. Dresar et al. [7,8] conducted experimental research on the two-phase boiling flows of nitrogen and hydrogen under steady low mass flow rate and heat flux conditions. The tests covered both the laminar and turbulent regions of the liquid phase. The variation of the Nusselt number showed that the two-phase heat transfer coefficient (HTC) peaks near the laminar-turbulent transition of the liquid phase, which coincides with a flow pattern transition from plug flow to slug flow. Tatsumoto [9,10]

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Nomenclature

a	thermal diffusivity ($m^2\ s^{-1}$)
A_C	equivalent cross-sectional area (m^2)
A	inner surface area of the test tube (m^2)
b	Laplace constant ($([\sigma/(g(\rho_l-\rho_v))]^{0.5}$)
D	outer diameter (m)
d_{max}	maximum inner diameter (m)
g	gravity acceleration ($m\ s^{-2}$)
G	mass flow flux ($kg\ m^{-2}\ s^{-1}$)
h	heat transfer coefficient ($W\ m^{-2}\ k^{-1}$)
ht	corrugation height (m)
Δh	the latent heat ($J\ kg^{-1}$)
I	current (A)
L	length of the test section (m)
$\dot{M}$	mass flow rate ($kg\ s^{-1}$)
n	increase exponent of HTCs with respect to the heat flux
P	absolute pressure (MPa)
P	helical pitch (m)
q	wall heat flux ($W\ m^{-2}$)
Q_{total}	total power input (W)
Q_L	heat leak from the surroundings (W)
Q_C	heat conduction along the axial direction (W)
R	the tube crest radius (m)
r	the tube groove radius (m)
T	temperature (K)
ΔT	temperature difference (K)
U	voltage drop (V)
$\dot{V}$	volumetric flow rate ($m^3\ s^{-1}$)
x	mass quality
z	the distance from the inlet of test section (m)

Dimensionless groups

Fr	Froude number
K_p	$p/[\sigma g(\rho_l-\rho_v))]^{0.5}$
K_λ	relative thermal conductivity, λ_w/λ_l
Nu	Nusselt number
Pe_*	modified Peclet number, $qb/(\Delta h\rho_v a_l)$

Greek symbols

δ	wall thickness (m)
θ	central angle (°)
λ	thermal conductivity ($W\ m^{-1}\ k^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)

Subscripts

1	before the test section
2	near the flow meter
ave	average
bottom	at the tube bottom
cal	calculated
l	saturated liquid
exp	experimental
middle-side	at the tube middle-side
sat	saturation
top	at the tube top
v	saturated vapor
w, i	inner wall
w, o	outer wall
z	distance from the test section inlet

investigated the subcooled LN_2 forced flow for both the non-boiling and boiling regions in a horizontal test tube and a vertical test tube respectively. Heat transfer curves were obtained for different flow velocities and subcoolings. Effects of the flow velocity and liquid subcooling on the inception fluxes of nucleate boiling, and the departure from nucleate boiling fluxes were discussed.

Although there are no well recognized correlations for the heat transfer characteristics of cryogenic fluids, several empirical correlations are proposed based on the increasing experimental researches on the flow boiling of cryogens. The correlation proposed by Shah [11] gave satisfactory agreement for nine out of eleven cryogenic flow boiling experiment datasets they collected. Steiner [12] collected the experimental data of saturated flow boiling of cryogens and filled the gaps with those of the ordinary fluids. Considering vertical and horizontal cases separately, he proposed the corresponding correlations for both the forced convection and nucleate boiling regimes for the vertical and horizontal tubes. Klimenko [13,14] proposed a generalized correlation with a maximum ±14.4% inaccuracy based on the experimental data of forced flow boiling heat transfer of cryogens and ordinary fluids in the vertical and horizontal tubes with the entire channel circumference wetted.

To the authors' best knowledge, most of the researches on the forced flow boiling of cryogenic fluids were devoted to the geometry of smooth tube, while there are relatively fewer studies on the enhanced tubes, let alone empirical correlations for the heat transfer prediction in enhanced tubes. The corrugated tube has been widely used in the fields of low-temperature heat exchangers and superconductors due to its good properties in flexibility and heat transfer enhancement, and it also meets the urgent requirement of high flux enhanced heat transfer in the electronic cooling and aerospace circumstances. There are basically two categories of heat transfer enhancement, the flow enhancement by disturbing the fluid, and the surface enhancement by increasing the heat transfer area. Although the rib height is small, the low rib corrugated tube in industrial applications normally increases the turbulence level of the flow and increases the heat transfer area at the same time. In single-phase flow the disturbances from the corrugated tube to the flow would reduce the boundary layer thickness and consequently enhance the heat transfer. In two-phase boiling where there are both convective and nucleate boiling heat transfer, however, the disturbances from the corrugated tube may decrease the degree of superheat in the boundary layer and suppress the nucleate boiling heat transfer. As a result, the effects of the corrugated tube to the two-phase boiling heat transfer depend on the operating conditions and need to be further clarified.

In this study, an experimental apparatus was setup for the investigation of forced flow boiling of LN_2 in a horizontal corrugated stainless steel tube. The forced flow boiling HTCs of LN_2 in a horizontal corrugated stainless steel tube were measured under two flow rates for a wide range of wall heat fluxes. The measured HTCs are then compared with four general existing correlations that were derived from extensive data banks of flow boiling heat transfer of many fluids in smooth tubes.

2. Experimental apparatus and test procedure

2.1. Experimental system

To investigate the heat transfer behavior of the forced flow boiling of LN_2 in a corrugated stainless steel tube, an open-type test rig was designed and constructed. Fig. 1 shows the flow diagram of the