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# Experimental study on the heat transfer characteristics of saturated liquid nitrogen flow boiling in small-diameter horizontal tubes

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## ABSTRACT

Experiments were performed to investigate the heat transfer characteristics of the saturated liquid nitrogen flow boiling in a horizontal tube with an internal diameter of 1.98 mm. The heat transfer coefficients were obtained within a wide range of operation conditions, i.e. inlet pressure from 230 to 420 kPa, mass flux from 200 to 690 $kg{\cdot}m^{-2}{\cdot}s^{-1}$, heat flux from 1.5 to 67.1 $kW{\cdot}m^{-2}$, and vapor quality from 0 to 0.81. In the low vapor quality region, heat transfer coefficients showed strong dependence on heat flux and pressure but varied little with mass flux or vapor quality, indicating the dominant role of the nucleate boiling over the convective evaporation. The influence of convective evaporation became noticeable in the intermediate-to-high vapor quality region. A modified correlation was proposed by including both the influences of the nucleate boiling and the convective evaporation, which could predict the experimental data with MAD of 16.4%.

## 1. Introduction

Two-phase flow boiling can use the sensible and latent heat of fluid to achieve a high heat transfer coefficient and an uniform temperature distribution, which makes it an ideal approach for high heat flux cooling. The flow boiling in small channels has many advantages such as high heat transfer coefficient, compactness, high operating pressure and low flow rate. It is widely used in the electronic equipment cooling [1], the environment cooling [2,3] and the heat exchangers in hydrogen energy storage systems [4]. The liquid nitrogen is colorless, odorless, non-combustible, non-flammable, and plentiful, which makes it an ideal cooling fluid in the 80 K temperature region. The study on flow boiling characteristics of the liquid nitrogen in small channels is important for the developement of highly-efficient and compact heat exchangers and also enriches our understanding of the dominant heat transfer mechanisms of the flow boiling in the low temperature region.

Many studies have been reported on flow boiling heat transfer in the horizontal small channels. A summary of previous studies on heat transfer coefficient of two phase flow in small channels is presented in Table 1. In most of those studies [5–11], the heat transfer coefficient was found to be dependent on heat-flux but independent on mass flux, indicating the dominant heat transfer mechanism was nucleate boiling. Wambsganss et al. [5] found the slug flow pattern presented in the small channels over a large range of parameters (heat flux (8.8–90.75 $kW/m^2$), mass flux (50–300 $kg/m^2s$), and equilibrium mass quality (0–0.9)) where the nucleation boiling dominated the heat transfer. They also found that the Lazarek and Black [17] correlation could predict the heat transfer coefficient with a mean deviation around 13%. This correlation expressed the Nusselt number as a function of the liquid Reynolds number and boiling number. Yun et al. [9] found that the nucleate boiling was much more dominant in microchannels with a smaller hydraulic diameter. Shiferaw et al. [11] indicated that when $x < 0.5$, the dominant heat transfer mechanism was nucleate boiling. For $x > 0.5$, the dry-out condition occurred.

In other studies [12–16], the local heat transfer coefficient was a function of vapor quality and mass flux in addition to wall heat flux. Experimental results in those studies generally showed the heat transfer coefficient decreased with the increase of vapor quality, which indicated the dominant role of the convective evaporation. Based on the diabatic two-phase flow pattern map, Sumith et al. [12] found the film evaporation (convective evaporation) dominated the heat transfer mechanism under conditions of mass flux from 23.4 to 152.7 $kg/m^2s$, heat flux from 10 to 715 $kW/m^2$, and vapor quality from 0 to 0.8. Lee and Mudawar [13] obtained the bubbly flow and nucleate boiling occurred only at low qualities ($x < 0.05$) corresponding to very low heat fluxes, which was also observed by Muwanga and Hassan [14] and Saitoh et al. [15]. At a high vapor quality ($x > 0.05$), the heat transfer mechanism was dominated by the annular film evaporation (convective evaporation). In and Jeong [16] found the heat transfer mechanism was different for different fluids under the conditions as shown in Table 1. The

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## Nomenclature

| | |
|---|---|
| $D$ | tube diameter, m |
| $G$ | mass flux, kg·m$^{-2}$·s$^{-1}$ |
| $\dot{m}$ | mass flow rate, kg·s$^{-1}$ |
| $h$ | heat transfer coefficient, W/(m$^2$K) |
| $q$ | heat flux, W/m$^2$ |
| $D_h$ | equivalent diameter, mm |
| $x$ | vapor quality |
| $H_{LV}$ | latent heat of vaporization, J/kg |
| $c_{p,L}$ | specific heat, J/(kg·K) |
| $T$ | temperature, K |
| $\Delta T$ | wall superheat, K |
| $P_H$ | heating power, W |
| $p$ | pressure, kPa |
| $L_q$ | heating length, m |
| $Bo$ | boiling number |
| $Bd$ | bond number |
| $We$ | Weber number |
| $Nu$ | Nusselt number |
| Re | Reynolds number |
| $z$ | tube position, m |
| Δp | pressure drop, kPa/m |
| S | suppression factor |
| F | enhancement factor |
| Co | confinement number |
| Pr | Prandtl number |
| Kp | pressure dimensionless parameter |
| X | Lockhart–Martinelli parameter |
| MAD | mean absolute deviation |
| MRD | mean relative deviation |
| $L_{sub}$ | length of subcooling segment, mm |

### Greek symbols

| | |
|---|---|
| $\rho$ | density, kg·m$^{-3}$ |
| $\sigma$ | surface tension, N·m$^{-1}$ |
| $\lambda$ | thermal conductivity, W/(m·K) |
| | viscosity, kg·m$^{-1}$·s$^{-1}$ |

### Subscripts

| | |
|---|---|
| in | inner surface of tube |
| out | outer surface of tube |
| w | wall |
| inlet | inlet of the test section |
| sat | saturation |
| $f$ | fluid |
| TP | two phase |
| V | vapor |
| L | liquid |
| pred | predicted |
| exp | experimental |
| t | total |
| eq | equilibrium |
| flash | flashing |
| NB | nucleate boiling region |
| FC | convective evaporation region |
| VO | pure vapor in channel |
| LO | pure liquid in channel |

**Table 1**
Summary of previous studies on flow boiling heat transfer characteristics.

| Author/year | Channel configurations | Fluids | Conditions |
|---|---|---|---|
| Wambsganss et al. [5], 1993 | 2.92 mm | R-113 | Heat flux: 8.8–90.75 kW/m$^2$, mass flux: 50–300 kg/m$^2$s, vapor quality: 0–0.9 |
| Yu et al. [6], 2002 | 2.98 mm | Water | Inlet temperature: ambient to 80 °C, mass flux: 50–200 kg/m$^2$s |
| Bao et al. [7], 2000 | 1.95 mm | R11, HCFC123 | Heat flux: 5–200 kW/m$^2$, mass flux: 50–1800 kg/m$^2$s, vapor quality: 0–0.9, system pressures: 200–500 kPa |
| Wu et al. [8], 2011 | 1.42 mm | CO2 | Heat flux: 7.5–29.8 kW/m$^2$, mass flux: 300–600 kg/m$^2$s, inlet temperature: −40 to 0 °C |
| Yun et al. [9], 2005 | 1.08–1.54 mm | CO2 | Heat flux: 10–20 kW/m$^2$, mass flux: 200–400 kg/m$^2$s, inlet temperature: 0, 5, 10 °C |
| Hamdar et al. [10], 2010 | 1 mm | HFC-152a | Heat flux: 10–60 kW/m$^2$, mass flux: 200–600 kg/m$^2$ s, |
| Shiferaw et al. [11], 2009 | 1.1 mm | R134a | Heat flux: 16–150 kW/m$^2$, mass flux: 100–600 kg/m$^2$s, pressures: 600–1200 kPa |
| Sumith et al. [12], 2003 | 1.45 mm/vertical | Water | Heat flux: 10–715 kW/m$^2$, mass flux: 23.4–152.7 kg/m$^2$s, vapor quality: 0–0.8 |
| Lee and Mudawar [13], 2005 | | R134a | Heat flux: 159–938 kW/m$^2$, vapor quality: 0.26–0.87 |
| Muwanga and Hassan [14], 2006 | 1.067 mm/horizontal | FC72 | |
| Saitoh et al. [15], 2005 | 0.51, 1.12, 3.1 mm/horizontal | R134a | Heat flux: 5–39 kW/m$^2$, mass flux: 150–450 kg/m$^2$s, inlet vapor quality: 0–0.2 |
| In and Jeong [16], 2009 | 0.19 mm/horizontal | R123, R134a | Heat flux: 10, 15, 20 kW/m$^2$, mass flux: 314, 392, 470 kg/m$^2$s, inlet vapor quality: 0.2–0.85 |

flow boiling of R123 was dominated by the convective evaporation. For R134a, the nucleate boiling was the dominant heat transfer mechanism until its suppression at the high vapor quality ($x > 0.6$).

Researchers have used different approaches with various levels of complexity to predict flow boiling heat transfer coefficients. Due to the enhancement of inertia effect and the weakening of gravity effect on the two-phase flow in small channels, the heat transfer characteristics is different from the conventional channels. In recent years, many studies proposed correlations for the flow boiling heat transfer coefficient in small channels. Some of the correlations were proposed by modifying the conventional channel correlations while the others were new correlations for the small channels.

For the nucleate boiling, Chen et al. [28] proposed the suppression factor $S$, which was defined as the ratio of the effective superheat to the total superheat of the wall. For the convective evaporation, Chen et al. [28] introduced an enhancement factor $F$, which is the ratio of the two-phase Reynolds number to the liquid Reynolds number. Some scholars modified the heat transfer correlations based on the Chen correlation. Bertsch et al. [29] introduced the influence of confinement number $Co$ to modify the enhancement factor $F$. Based on the Martinelli parameter $X$ according to Lockhart and Martinelli [31], Zhang et al. [30] modified the enhancement factor $F$. Saitoh et al. [32] pointed out that the surface tension effect gradually increases with the decrease of channel diameters. They modified the coefficient $F$ with vapor Weber number $We_{VO}$.

Some scholars developed new correlations for the heat transfer characteristics in small channels. Tran et al. [33] found the main heat transfer mechanism in small channels was the nucleate boiling. Based on the influence of heat flux, surface tension and fluid properties, the heat transfer coefficient was related to the boiling number $Bo$, Weber number $We$, and liquid vapor density ratio $\rho_L/\rho_V$. Warrier et al. [34] developed the heat transfer correlation based on boiling number $Bo$ and