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# Experimental investigation on flow boiling heat transfer in conventional and mini vertical channels

Qi Lu, Deqi Chen *, Chong Li, Xueqiang He

*Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Ministry of Education, Chongqing University, Chongqing 400044, China*

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## ABSTRACT

An experimental investigation was carried out to study the flow boiling heat transfer mechanism in the vertical channels with different inner diameters. The heating section of the test-section was stainless steel tube, and the transparent sections were equipped at inlet and outlet of the test-section, respectively. The flow patterns at outlet were recorded by a high speed camera, and the corresponding experimental parameters were measured simultaneously. In this study, the characteristics of flow boiling heat transfer with different inner diameters, inlet water temperatures, mass fluxes, and heat fluxes were analyzed in detail. Moreover, a modified correlation on the Chen correlation was proposed to predict the heat transfer coefficients in the vertical channels, and this correlation was verified with good agreement.

## 1. Introduction

Flow boiling heat transfer systems are widely used in industries, such as aerospace, electronics, and chemistry. Due to the effective heat removal and maintenance of relatively uniform surface temperatures during the heat transfer process, the flow boiling heat transfer in mini scale channels has received much attention.

Over the years, there has been much debate about what identifies a channel size as conventional or mini since the heat transfer and flow characteristics can be different over the ranges of millimeter to sub-millimeter size. A critical diameter of 3 mm was suggested by Kandlikar [1] for the conventional-to-mini channel threshold. A threshold of 6 mm for conventional-to-mini scale channel was proposed by Mehendal et al. [2]. Meanwhile, Chen et al. [3] proposed that the channels with the diameters of 1.10 mm and 2.01 mm exhibited strong “mini channel characteristics”. However, Ribatski et al. [4] suggested that these criterions adopted here did not take into account differences in the two-phase flows and heat transfer processes in conventional and mini scale channels. Kew and Cornwell [5] proposed an approximate physical criterion for conventional-to-mini scale channel threshold diameter based on the confinement of a growing bubble within a channel as follows:

$$N_{conf} = \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)D_{in}^2}} \tag{1}$$

where $N_{\mathrm{conf}}$ is the confinement number; $\sigma$ is the surface tension (N/m); $g$ is the acceleration of gravity ($\mathrm{m^2/s}$); $D_{\mathrm{in}}$ is the inner diameter (mm); $\rho_l$ is the density of liquid phase ($\mathrm{kg/m^3}$), and $\rho_g$ is the density of vapor phase ($\mathrm{kg/m^3}$). As mentioned by Kew and Cornwell [5], the critical $N_{\mathrm{conf}}$ for conventional-to-mini scale channel is about 0.5, therefore the critical diameter between conventional and mini scale channel is about 5 mm for saturated water (0.101 MPa).

Widely accepted is that two mechanisms are considered to dominate flow boiling heat transfer: the nucleate boiling and the forced convection with evaporation. As described by Charnay et al. [6], the nucleate boiling was dependent on the heat flux and the saturation pressure. However, the forced convection with evaporation was related to the conduction and convection through the liquid film, which was dependent on the mass flux and the vapor quality. As proposed by Tran et al. [7], the boundary between the nucleate boiling and the forced convection with evaporation was a function of the wall superheat. The nucleate boiling region occurred at high wall superheat, while the forced convection with evaporation region occurred at low wall superheat. These mechanisms could coexist with vapor quality as suggested by Vlasie et al. [8] and Collier and Thome [9], where the heat transfer coefficient depended on heat flux, mass flux and vapor quality. Generally, these boiling mechanisms were usually assumed to be independent of each other due to the simplicity of discussion about flow boiling heat transfer. Some authors (Tran et al. [7], Bao et al. [10] and Ali et al. [11]) suggested that the major trend of flow boiling heat transfer in mini-channel was that the heat transfer coefficients were only a function of heat flux, and largely independent on vapor quality or mass flux, which indicated that the nucleate boil-

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* Corresponding author.
*E-mail address:* chendeqi@cqu.edu.cn (D. Chen).

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## Nomenclature

*General symbol*

| | |
|---|---|
| $N_{conf}$ | the confinement number |
| $D_{in}$ | the inner diameter (mm) |
| $G$ | the mass flux (kg/m$^2$ s) |
| $T$ | the temperature (°C) |
| $\rho$ | the density (kg/m$^3$) |
| $U$ | the voltage (U) |
| $I$ | the current (A) |
| Q | the power (kW) |
| $q$ | the heat flux (kW/m$^2$) |
| $\phi$ | the power density (W/m$^3$) |
| $C$ | the perimeter of the inner cross section (m) |
| $L$ | the length of the heating section (m) |
| $r$ | the radius (m) |
| $A$ | the area of the inner cross section (m) |
| $z$ | the distance (m) |
| $a$ | the constant |
| $k$ | the thermal conductivity (W/m K) |
| $h$ | the heat transfer coefficient (kW/m$^2$ K) |
| $x_e$ | the equilibrium quality |
| $H$ | the enthalpy (J/kg) |
| $H_{fg}$ | the latent heat of vaporization (J/kg) |
| $\Delta T_{sat}$ | the wall superheat (K), $T_w - T_{sat}$ |
| $\Delta P_{sat}$ | the difference in vapor pressure corresponding to $\Delta T_{sat}$ (kPa) |
| $P$ | the pressure (kPa) |
| $Re$ | the Reynolds number |
| $Pr$ | the Prandtl number |
| $c_p$ | the specific heat (J/kg K) |
| $F$ | the enhancement factor |
| $S$ | the suppression factor |
| $X_{tt}$ | the Martinelli parameter |
| $Bo$ | the boiling number |
| $M$ | the molecular weigh |

*Greek letters*

| | |
|---|---|
| $\sigma$ | the surface tension (N/m) |
| $\mu$ | the dynamic viscous (Pa·s) |
| $g$ | the acceleration of gravity(m$^2$/s) |

*Subscripts*

| | |
|---|---|
| tot | total |
| w/wall | wall |
| in | inner |
| m | mixture |
| sat | saturated |
| v | vapor phase |
| $l$ | liquid phase |
| tp | two-phase |
| b | bulk |
| cr | critical |
| fc | forced convection |
| pb | pool boiling |
| exp | experimental value |
| pre | predicted value |

ing mechanism dominated in mini-channel. In addition, Huo et al. [12] experimentally investigated the boiling heat transfer in vertical mini-channels with R134a as the working fluid. It was found that the dominant characteristics of the heat transfer was the nucleate boiling as the vapor quality was less than 20%–30% with the channel diameter of 2.01 mm and 40%–50% with the channel diameter of 4.26 mm. However, Lin et al. [13] demonstrated that both mechanisms of the nucleate boiling and the forced convection with evaporation occurred in mini-channels. All the works mentioned above used hydrocarbon fluids, which were much different from water in physical properties such as the boiling point and the latent heat of vaporization. The research conducted by Qu and Mudawar [14] and Bang et al. [15] proposed that the heat transfer coefficient generally presented a positive relationship with the mass flux and the vapor quality in the case of water used for the working fluid, which indicated that the forced convection with evaporation dominated attributed to the considerable vaporization latent heat of water. Also, Karayiannis et al. [16] suggested a progression from the nucleate boiling to the forced convection with evaporation as the heating length increased. Sumith et al. [17] carried out an experiment to research the flow boiling heat transfer in a vertical channel with inner diameter of 1.45 mm. It was concluded that the heat transfer mechanism deviated from the nucleate boiling and closely resembled the forced convection with evaporation as flow pattern transferred to annular flow. Also, it was possible for nucleate boiling to continue even in the liquid film of the wavy-annular flow as the liquid film was thick enough.

As is known to all, the region of two-phase flow initiates at the onset of nucleate boiling (ONB) where nucleation requires a high degree of the wall superheat. As proposed by Piasecka and Poniewski [18], a considerable rise above the saturation point of wall temperature could occur before boiling with certain conditions. This temperature overshoot, also known as “superheated excursion” and “nucleation hysteresis” was conspicuous as for highly wetting dielectric fluids (e.g., refrigerants). Lie and Lin [19] found that a significant wall temperature overshoot of about 20 K at ONB was found for R134a in a horizontal narrow annular duct. However, the wall temperature overshoot was just 3 K at ONB with the cyclohexane as the working fluid as proposed by Liu and Bi [20].

The effect of hydraulic diameter on the heat transfer coefficient is somewhat inconsistent in published literatures. Owhaib et al. [21] suggested that the reduction of the hydraulic diameter (circular channel) caused the heat transfer coefficients to increase. Saitoh et al. [22] studied the boiling flow in three channels with diameters of 0.51 mm, 1.12 mm, 3.1 mm, respectively. The results showed that the maximum heat flux increased with the hydraulic diameter reducing. Also, the maximum heat flux occurred for lower quality as the hydraulic diameter reducing. Additionally, Sobierska et al. [23] proposed that the reduction of the hydraulic diameter strongly enhanced the influence of the vapor quality on the heat transfer coefficient. In contrast, Dupont and Thome [24] showed that the heat transfer coefficient decreased with hydraulic diameter increasing from 0.5 mm to 2 mm as $x > 0.18$.

In general, it is crucial to distinguish the stable boiling during flow boiling heat transfer experiments, but there is not a theoretical criteria to distinguish them. Consolini and Thome et al. [25] indicated that the heat transfer coefficient for stable boiling gradually increased with the vapor quality up to a high value whilst it did not change obviously. As mentioned by Karayiannis et al. [16], the local wall temperature and heat transfer coefficient could highly fluctuate for unstable boiling. Moreover, the liquid film