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Onset and departure of flow boiling heat transfer characteristics of cyclohexane in a horizontal minichannel

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ABSTRACT

The flow boiling behavior of cyclohexane was experimentally investigated in a horizontal minichannel with inner diameter of 2.0 mm. The nucleation hysteresis phenomena at onset of nucleate boing (ONB) and characteristics at departure of flow boiling were focused on. Both the temperature overshoot due to nucleation hysteresis and wall superheat to maintain boiling conditions decreased with the increasing pressure. The nucleation hysteresis can be clearly observed at pressure of (1.0 and 2.0) MPa, but disappeared at 3.0 MPa. A wall temperature decrease phenomenon (TDP) was found to occur just before flow boiling heat transfer deterioration (HTD). The magnitudes of TDP would be less than 10 °C, but bigger than the temperature overshoot of about 3 °C at ONB. Wherever HTD happened at the saturation boiling conditions with high or low vapor quality ranging from 0 to 1, the TDP were observed, but suppressed by the increasing pressure. Accordant with nucleate hysteresis, the TDP were clearly recorded at $P = 1.0$ and 2.0 MPa, but disappeared at 3.0 MPa. The mechanism of TDP before HTD at flow boiling condition, a problem needed extensive focus investigation, may give a better understanding or even a universe CHF mechanism for both dryout and burnout conditions.

1. Introduction

The flow boiling heat transfer in mini/micro channel has been focused and widely researched in the last two decades [1–8]. The important processes and engineering issues including flow distribution, flow instability, nucleation processes, boiling heat transfer and pressure drop were reviewed by Bergles et al. [2] when channel diameters decrease for the design of practical systems. Kandlikar [3–6] investigated and reviewed fundamental issues of flow boiling and heat transfer mechanism in mini/micro channels. The criteria to recognize and differentiate the onset of subcooled boiling, partial boiling, fully developed boiling, and significant void flow were recommended and validated [3]. The effect of surface tension on flow pattern, flow instability and pressure drop fluctuations were discussed in the small diameter channel heat exchanger [4]. As the channel diameter became smaller, larger wall superheat were required for nucleation in microchannels [5]. Correlations to predict heat transfer coefficients for laminar flow, transition flow, and low laminar flow ($150 < Re_{LO} < 450$) and deep laminar flow ($Re_{LO} \leqslant 100$) were recommended or proposed for mini/micro channels [6]. Kim and Mudawar [7,8] conclusively reported saturation flow boiling performance in mini/micro channels for 18 working fluids, and proposed generalized correlations to predict dryout incipience qualities, two phase heat transfer coefficient in nucleate boiling dominated and convective boiling dominated heat transfer regimes.

The mini/micro channels are widely used as heat sinks [1] in aerospace flight, electrical cooling, and so on. The space and/or weight constraints in the small scale devices make the cooling channel much tinier, and also the small passages may provide a high performance. In applications for which the coolant enters the channel in the subcooling condition, the designer of the heat exchanger expects that the subcooled boiling occurs in the earliest point of the channel without drying out or departure of nucleate boiling (DNB) in the end of the channel. The flow boiling heat transfer processes are usually used in the high heat flux removal applications [2]. However, the underlying mechanism of the flow boiling, especially the subcooled flow boiling in mini/micro channel are still an open question.

As be well known that at the beginning of flow boiling process at start-up, it requires a higher degree of wall superheat to nucleate the bubble [3]. Once the boiling is initiated, the required superheat to sustain the bubble activity is lower. This behavior is known as the hysteresis effect, which is significant in highly wetting liquids such as refrigerants. Lie and Lin [9] found a significant wall temperature overshoot of approximately 20 °C at onset of nucleate

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Nomenclature

D	internal diameter (m)
G	mass velocity (kg/m^2 s)
h	enthalpy (J/kg)
I	electrical current (A)
L	heated length (m)
M	mass flow rate (g/s)
P	pressure (MPa)
q	heat flux (W/m^2)
Q	heating power (W)
T	temperature (°C)
U	voltage (V)
x	vapor quality (–)

Greek symbols

ρ	density (kg/m^3)
η	heating efficiency

Subscripts

exp	experimental
s	saturation
w	wall
inlet	channel inlet
i	at *i*th thermocouple point

boiling (ONB) for the subcooled boiling of R-134a in a horizontal narrow annular duct with gap of (1.0 and 2.0) mm. Piasecka and Poniewski [10] investigated the subcooled nucleation hysteresis in a one-side heated narrow rectangular channel with 1 mm depth, 40 mm width and 360 mm vertical length. The temperature distributions of the heated wall were obtained from liquid crystal thermography. The boiling incipience was recognized as a sudden drop of the wall temperature. Though the boiling incipient and the nucleation hysteresis phenomena has been investigated and reported over two decades [11–13], only a few articles were published in literatures because the tiny wall temperature overshoot could be hardly caught and found by experimental investigation.

Mudawar and Bowers [14] figured the drastically different flow patterns as well as unique CHF trigger mechanisms at low and high mass velocity. The liquid film dryout is the mechanism responsible for the relatively low CHF values associated with saturated boiling in long tubes with low inlet subcooling. High CHF values can occur in the subcooled boiling at high mass velocity flow in a short tube with high inlet subcooling and is commonly refered as DNB. Though there are many famous CHF correlations (such as correlations from Katto and Ohno [15], Shah [16], Qu and Mudawar [17], Wojtan et al. [18], and Zhang et al. [19]) which can well predict the CHF values for conventional size channel and mini/micro channel, the CHF mechanism, especially for subcooled boiling, is not well understood yet. It was proposed in Deng's thesis [20] that the CHF could occur in any one of the flow patterns, and the basic mechanism of CHF could be the same in both the subcooled and saturated boiling regimes. A continuous CHF correlation was obtained for various boiling regimes by a systematic investigation on the effect of major variables on CHF, such as pressure, mass velocity, inlet or outlet quality, and test section geometry.

Visualization investigation on flow boiling of water by Wu and Cheng [21] reported long-period/large-amplitude fluctuations at onset of boiling with two-phase flow and single-phase liquid flow appearing alternatively with time in the microchannels. The phase differences between the fluctuations of pressure drop and mass flux were identified as the reason to sustain the flow instability. The follow up research by Wang and Cheng [22] found that the occurrence of microbubble emission boiling (MEB) can remove high heat flux of 14.41 MW/m^2 at a mass flux of 883.8 kg/m^2 s with only a moderate rise in wall temperature.

In this paper the flow boiling behavior of cyclohexane was investigated in an electrically heated minichannel. It was focused on the onset and departure of flow boiling heat transfer characteristics. The heat transfer deterioration due to the departure of flow boiling includes dryout in the saturation boiling regime and departure of nucleate boiling in the subcooled boiling regime. Cyclohexane was used as a model substance of endothermic hydrocarbon fuel, whose heat transfer characteristics were investigated by our previous literatures [21–23]. The research on flow boiling of cyclohexane could improve the understanding of relevant behavior of endothermic fuel, which is potential to be used as propellant and coolant in the regeneratively cooled hypersonic vehicles. Some novel findings may be significant for the uncovering of the universe mechanism of heat transfer deterioration for subcooled boiling and saturated boiling.

2. Experimental setup

The flow boiling heat transfer characteristics of cyclohexane were experimentally investigated in an electrically heated horizontal minichannel (heated length L: 360 mm; internal diameter D: 2.0 mm; wall thickness: 0.5 mm). The minichannel with material of nickel alloy GH3128, manufactured by China Iron & Steel Research Institute Group (Beijing, China), can work at wall temperature up to 1000 °C. The elemental composition of the GH3128 material is shown in Table 1. The average roughness (Ra) of the test channel inner surface is measured as 0.8 μm by 3D measuring Laser Microscope Olympus LEXT OLS4000. The stated purity of the used cyclohexane (from Tianjin Fuchen Chemical Agent) is larger than 99.5 wt.%. The experimental facilities and diagrams of the test section were shown in Fig. 1, and also described in detail in previous literatures [23–25].

The cyclohexane was provided by a constant volume pump (Elite P500 from China) with all the fluid out of the pump flowing through the test channel. Therefore the flow rates for the experiments were directly controlled by the pump. The fluid flow stability of the pump is within ±0.5%. A Coriolis mass flow meter with accuracy of ±0.1% at the inlet of test section was used to measure the mass velocity which was controlled at 1.0 g/s (318 kg/m^2 s). Electrical insulator were designed and inserted into the flow passage to isolate the alternate current (AC) electrically heated test section. The electrical current and voltage across the test section were measured to obtain the heating power. The outlet pressure and pressure drop across the test section were measured by Rosemont 3051 transducers. Before the fluid pressure controlled

Table 1
Elemental composition of the GH3128 material.

Element	wt.%	Element	wt.%	Element	wt.%
C	⩽0.05	Al	0.40–0.80	Ce	⩽0.050
Cr	19.0–22.0	Ti	0.40–0.80	Mn	⩽0.50
Ni	>55.0%	Fe	⩽2.0	Si	⩽0.80
W	7.5–9.0	B	⩽0.005	P	⩽0.013
Mo	7.5–9.0	Zr	⩽0.06	S	⩽0.013