Applied Thermal Engineering 113 (2017) 831–842

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Flow boiling of ammonia and flow instabilities in mini-channels

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HIGHLIGHTS

- Flow boiling visualization and measurement of ammonia in minichannels are studied.
- Reverse flow occurs periodically in the mini-channels.
- Both damped and stable oscillations of pressure drop are identified.
- High-frequency oscillation occurs at the crest of the low-frequency wave.
- Frequency of the oscillation increases with mass flux and working temperature.

ARTICLE INFO

Article history:
Received 23 January 2016
Revised 10 November 2016
Accepted 13 November 2016
Available online 14 November 2016

Keywords:
Mini-channel
Two-phase flow
Ammonia
Flow boiling instability
Flow pattern

ABSTRACT

A simultaneous visualization and measurement study has been carried out to investigate the flow boiling and two-phase flow instabilities of ammonia in a mini-channel evaporator at various heat and mass fluxes. The evaporator consisted of 4 parallel 1 × 1.1 mm channels with a uniformly heated length of 250 mm. The visualization study showed that periodic reverse flow occurred in the mini-channel evaporator with liquid rewetting stage and annular film evaporating stage repeated alternately. Both damped and stable oscillations of pressure drop, wall temperature and system pressure were observed. The liquid rewetting stage approximately coincided with the decreasing stage of system pressure. Three typical two-phase flow patterns: bubbly flow, elongated bubble/slug flow and annular flow were identified. Low-frequency high-amplitude oscillation and high-frequency low-amplitude oscillation were identified through wavelet analysis. The high-frequency oscillation mainly occurred at the wave crest of the low-frequency oscillation. In addition, high-order harmonics were found in almost all the low-frequency oscillation waves. The effects of mass flux and saturation temperature on flow boiling instabilities were also investigated.

1. Introduction

With rapidly increasing demand of high power electronic devices in national-defense, space, electronic communication applications, new innovative cooling technologies have become particularly desirable to remove the dissipated heat for these devices. In general, the local heat dissipation rate of these electronic devices is >100 W/cm^2 [1]. As one of the effective methods for high heat flux cooling applications, micro/mini-channels cooling technologies with two-phase flow have attracted copious of investigations in recent years. Heat sinks with micro/mini-channels have many advantages, such as high heat transfer coefficients, small thermal resistance, compact physical size and low capital cost, reduced fluid inventory requirement. However, flow boiling instabilities often appear in micro/mini-channel heat sinks. Qu and Mudawar [2] explored hydrodynamic instability of water in a copper micro-channels heat sink containing 21 parallel 231 × 713 μm micro-channels. They identified two types of two-phase hydrodynamic instability: severe pressure drop oscillation and mild parallel channel instability. Wu [3,4] performed simultaneous visualization and measurement investigation of water in parallel micro-channels. The study showed that once flow boiling was established, two-phase flow and single-phase liquid flow appeared alternatively with pressure drop and mass flux oscillated in different phases. Wang et al. [5,6] investigated flow boiling of water in both parallel channels and a single channel with a hydraulic diameter of 187 μm. Two unstable flow boiling regimes, with long-period oscillation and short-period oscillation in pressure were identified. Hetsroni et al. [7] found that the temporal behavior of temperature fluctuations

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.093
1359-4311/

Nomenclature

Cp	specific heat (J/(kg K))
h_{fg}	latent heat of evaporation (J/kg)
L	channel length (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of channels (–)
P	perimeter (J/kg)
q	heat flux (W/m^2)
T	temperature (°C)
x	vapor quality (–)

Greek symbols

φ	heat transfer ratio

Subscripts

ch	channel
fin	fin
h	heated
q	quartz glass
sat	saturation
w	wall

corresponds to that of pressure fluctuations. The amplitude and frequency of these two fluctuations increased with heat flux. Huh et al. [8] agreed that the oscillation was due to the internal compressible volume of very long channel ($L/D_h > 150$). Kandlinkar [9,10] comprehensively investigated flow boiling instabilities in micro-channels and mini-channels. They concluded that all the critical heat flux (CHF) studies in their paper were affected by flow instabilities, and the CHF suffered severe reduction due to flow instabilities [11]. This was also evidenced by Qu [12], Brutin [13] and Kaya et al. [14]. Kuo [15] first tested the effects of system pressure on flow boiling instabilities in micro-channels. With system pressure increasing from 50 to 205 kPa, the boiling instabilities were significantly decayed and CHF was extended to high mass qualities. Barber et al. [16,17] conducted simultaneous measurement of local heat transfer coefficient in conjunction with local flow visualization in a rectangular micro-channel using n-pentane as the working fluid. They affirmed that the frequency of the flow instability in a micro-channel was driven by both the bubble dynamics and the channel wall thermal properties.

It should be noted that all the studies reviewed above were performed at low system pressures with water as the mostly used fluid. As shown by Kuo [15], the system pressure has a favorable effect on the system stability. It is reasonable to wonder that whether flow oscillation occurs in high pressure systems. Bowers et al. [18] reported reverse flow in a micro-channel evaporator used for R410A residential A/C system. Szczukiewicz et al. [19] identified significant flow instabilities, back flow, and non-uniform distribution of R245fa, R236fa, R1234ze in a 100 × 100 um parallel micro-channels. His study showed that the system maintained a better heat transfer performance without reverse flow. Zhang et al. [20] investigated R134a flow instabilities in a two-loop refrigeration system. Two different active control schemes are studied theoretically to stabilize the two-phase system. Tuo [21] explored periodic reverse flow and associated boiling fluctuation in a micro-channel evaporator used in a R134a air conditioning system. The evaporator performance and the system efficiency improved when venting ports were added on the ends of the inlet header [22]. There is no doubt that flow instabilities can also occur in high pressure systems.

Because of excellent properties, for example, large latent heat of vaporization, high thermal conductivity, ammonia has been widely used in space applications. However, only few published studies are available for mini/micro-channels in recent years. Da Silva Lima et al. [23] investigated flow boiling of ammonia inside a 14-mm inner diameter, horizontal smooth tube. Stratified-wavy, slug-stratified-wavy, slug, intermittent and annular flow were identified. Field [24] tested adiabatic two-phase flow pressure drop of ammonia in a rectangular micro-channel with D_h = 148.0 μm. A new correlation accounting for surface tension and flow regime was presented. Maqbool et al. [25,26] measured two-phase pressure drops of ammonia at a wide range with inner diameter of 1.70 mm and 1.224 mm. Similarly, a new correlation for two-phase flow pressure drop was presented. However, few studies concentrating on ammonia flow instabilities in micro-channel system were reported. Due to its inherent thermal physical properties, extensive applications and the practical merits of micro/mini-channel heat exchangers, it necessary to investigate the flow boiling instabilities of the ammonia system with micro/mini-channel heat exchangers.

This paper mainly focuses on the flow boiling and its instabilities of ammonia in an aluminum mini-channel evaporator. The evaporator contains 4 parallel 1 × 1.1 mm channels with a uniformly heated length of 250 mm. Visualization and measurement studies are conducted simultaneously. Oscillations of pressure drop, wall temperature and system pressure are observed. Fourier analysis and wavelet analysis are both presented. The effects of saturation temperature and mass flux on the flow instability are investigated.

2. Experiment setup and measurement

2.1. Experimental facility

Fig. 1 shows a schematic diagram of ammonia two-phase flow system. It consists of a storage tank, a variable speed gear pump, a filter, a pre-heater, three needle valves, a buffer tank with a film heater, a mini-channel evaporator, and a condenser with a water chiller. All the pipes, the evaporator and the buffer tank are insulated by thermal insulations to prevent heat loss. The system pressure is maintained by the buffer tank which is heated by a low power film heater. A K-type thermocouple is pasted on the bottom of the buffer tank for safety. The ammonia used in this experiment is pure with concentration better than 99.999%.

2.2. Test section and measurement

The test section schematic diagram is shown in Fig. 2. Viewed from side in Fig. 2(a), the test section contains a cover flange, a piece of quartz glass plate, an aluminum mini-channel evaporator, Bakelite housing, a copper block with holes and slots, and a steel support plate. The quartz glass plate facilitates the direct visual access to the two-phase flow in the channels. The evaporator is formed by cutting 4 of 1.0 mm wide and 1.1 mm deep slots into the aluminum plate's top surface. The detailed partial structure of the evaporator is shown in Fig. 2(b) and the dimensions are given in Table 1. Below the evaporator, nine K-type thermocouples are inserted along the center line to measure the temperature distribution of the mini-channel evaporator. Further below is the copper block with 8 holes drilled into the bottom surface to accommodate the cartridge heaters. Both on the top and bottom