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Enhanced condensation heat transfer for dielectric fluid within microchannel heat sink

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ABSTRACT

This study experimentally investigates the condensation of dielectric fluid HFE-7100 within a microchannel heat sink with a hydraulic diameter of 800 μm at a fixed outlet pressure of 110 kPa. The corresponding mass fluxes ranges from 100 to 300 kg m^{-2} s^{-1} and the vapor mass quality varies from 0.1 to 0.9 with inclinations ranging from −90° (vertical downward) to 90° (vertical upward). In addition, the present study also proposes a novel condensate drainage concept by imposing a micro drainage channel sitting near the corner of the conventional micro-channel to enhance the condensation heat transfer performance. Through this micro drainage design, the condensate will be pulled into the drainage channels effectively, thereby resulting in reducing liquid film thickness and enhancing the two phase heat transfer performance accordingly. The results show that the micro-channel heat sink with micro-drainage channel can enhance the heat transfer coefficient in the order 5–15%. In addition, the frictional pressure gradient will be decreased by about 5–25%. For a lower mass flux of the conventional microchannel, the flow visualization indicated that the elongated vapor slug flow patterns may occasionally reveal appreciable stalling or even reversal against main flow direction subject to vertically arrangement, yet this phenomenon is seldom seen for the proposed micro drainage channel.

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1. Intoduction

With the advent of micro/nano technology, the miniature of electronic devices also accompanies with the rise of power density. This eventually incurs the development of innovative and efficient cooling methods to maintain the device junction temperatures below certain threshold values. Hence, the working fluids had been migrated from air, single phase liquid, to two-phase heat transfer as higher heat flux is imposed. Moreover, more advanced cooling configurations had been proposed. For high flux cooling, as pointed out by a recent review by Kim and Mudawar [1], three cooling configurations had attracted the most attention: mini/micro-channel, jet and spray. Among them, two-phase mini/micro-channel heat sinks are mostly adopted for easier fabrication, and small coolant inventory [1]. Kim and Mudawar [2] also reviewed and illustrated the versatility of mini/micro-channel design, including isolated tubes, tubes that are soldered upon a heat dissipating surface, and channels that are formed into a conducting substrate, and various shapes of microchannel (rectangular, square, triangular, trapezoid, diamond, and the like).

Notice that the microchannel condenser had been implemented successfully in automobile industry and there had been numerous studies related to the condensation phenomena in micro channels. Typical reviews by Garimella [3], and Ribatski, and Da Silva [4] had summarized the related developments in condensation within microchannels. Note that based on these existing reviews, the majority of the relevant studies in association with condensation in microchannels focused on either the flow pattern with or without heat removal, frictional performance, or condensation heat transfer performance pertaining to shape configurations. For example, Shin and Kim [5] investigated the flow condensation of the refrigerant R134a inside a horizontally round tube with a diameter of 691 μm. The associated change of Nusselt number and pressure drop in various qualities were reported. Their results showed that Nusselt number and pressure drop is increased with increasing quality and mass flow rate. No apparent effect of the heat flux was found in the heat transfer coefficient and frictional pressure drop. Moreover, large pressure drop fluctuation was noted, except in the high quality flow range. They attributed the fluctuation to the surface tension. The effect of geometry on flow condensation in the mini-channels was reported by Shin and Kim [6]. They found a clear increment in heat transfer coefficient and pressure drop as the hydraulic diameter is decreased. With the presence of the surface tension, the square channels showed a

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Nomenclature

A	area of micro-channel heat sink (m^2)
A_w	total surface area of the micro-channel (m^2)
Bo	Bond number
C_p	specific heat of HFE-7100 (J kg^{-1} K^{-1})
d_i	diameter (hydraulic) (m)
G	mass flux (kg m^{-2} s^{-1})
h_{tp}	two-phase condensation heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity of micro-channel heat sink (W m^{-1} K^{-1})
$\dot{m}$	mass flow rate of HFE-7100 (kg s^{-1})
Q	condensation heat transfer rate (W)
Q_{input}	input power from electric heater (W)
t	thickness of the micro-channel heat sink (m)
i_{fg}	latent heat of HFE-7100 (J kg^{-1})
x_{avg}	average mass quality
x_{in}	inlet vapor mass quality
T_{upper}	the upper temperature of micro-channel heat sink (K)
T_{lower}	the lower temperature of micro-channel heat sink (K)
T_{sat}	saturated temperature of HFE-7100 (K)
T_{wall}	the surface temperature of micro-channel (K)

Greek symbols

α	void fraction
ρ	density (kg m^{-3})
θ	inclined angle (°)
σ	surface tension (Pa s)
ΔT_{sub}	inlet subcooling of HFE-7100 (K)
ΔT_m	effective mean temperature difference (K)
ΔP	pressure drop (Pa)
Δx	the thickness between the position of measured upper temperature and the measured lower temperature

Subscript

a	accelerational component
drainage	drainage channel
f	frictional component
G	gas phase
g	gravitational component
L	liquid phase
t	total

higher heat transfer coefficient than that of the circular channels for a similar hydraulic diameter with a lower mass flux. However, with increasing the mass flux, the heat transfer coefficient of the square channels was lower than those of the circular channels. Garimella [7] conducted flow visualization of the condensation flow pattern for various tube geometries and hydraulic diameters using R-134a. The observed flow patterns were categorized into four different flow regimes: annular flow, wavy flow, intermittent flow and dispersed flow. The results showed that the portions of the intermittent and annular flow regimes were increased with decreasing hydraulic diameter, signifying an increasing influence of surface tension. Also, the wavy flow regime is progressively decreased and eventually disappeared with decreasing hydraulic diameter, giving way to the annular flow regime and negligible influence of gravitational force at a small diameter. Tube geometry, however, was found to be less significant than hydraulic diameter in determining the condensation flow pattern. Mghari et al. [8] investigated the steam condensation in a non-circular microchannel by numerical method. Results were given for different microchannels shape, aspect ratio, various inlet vapor mass quality

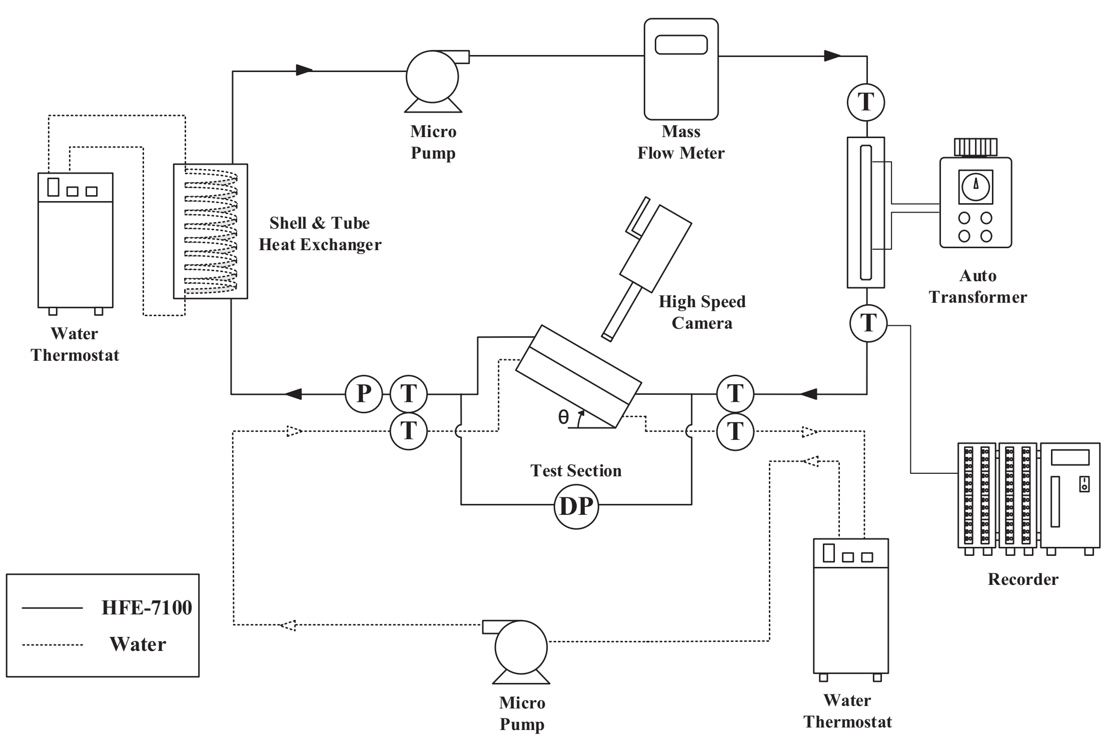

Fig. 1. Experimental setup.

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