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EFFECT OF INLET SUBCOOLING ON FLOW BOILING BEHAVIOUR OF HFE-7200 IN A MICROCHANNEL HEAT SINK

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1. INTRODUCTION

Miniaturised electronics pose challenging thermal demands, not only at chip-level power dissipation but also at the complete system-level heat rejection in modern electronic packages. Chip-level power densities are projected to be as high as 4.5 MW/m^2 in computer systems by 2026 [1] and have been reported to exceed 10 MW/m^2 in power modules for defence applications [2]. For instance, microwave power modules used in critical applications such as radar systems and satellites operate at high frequencies to improve dynamic response and reduce component size, albeit at the cost of device efficiency. For a typical efficiency of 20 % and input power of 850 W, almost 700 W of waste heat must be rejected from the system into the immediate environment, proving to be particularly challenging in aerospace applications where air-cooling is preferred. Flow boiling in microchannels is regarded as a promising cooling solution [1] for microelectronic systems where surface temperatures are limited to between 85 – 125 °C. The effect of various operational parameters on the performance of the cooling system must be well understood to facilitate successful integration of the developed technology into real-life systems. One of the important parameters in microchannel flow boiling is the degree of subcooling condition at the inlet of the heat sink as it affects the conditions for bubble nucleation, subsequent bubble growth, saturation conditions as well as flow reversal and instabilities in the channel. Deng et al. [3] studied the effect of inlet subcooling at 10 and 40 K of ethanol and found larger flow boiling heat transfer coefficients at higher degree of subcooling but concluded that subcooling had a negligible effect on pressure drop. On the contrary, in the subcooled boiling study of HFE-7100 in [4], heat transfer coefficient and pressure drop both experienced a slight decrease at higher degree of subcooling. Although considerable effort has been dedicated to the development of microchannel evaporator modules for high heat flux cooling, little attention has been paid to the study of integrated thermal management loops complete with a suitably-sized condenser. The degree of subcooling used will influence the design and size of both the evaporator and the condenser. In this study, the effect of inlet subcooling on the flow boiling characteristics of a microchannel evaporator, developed for the cooling of high heat flux devices using dielectric refrigerant HFE-7200 was investigated.

2. METHODOLOGY

The experimental facility is shown in Fig. 1. The main loop consists of a reservoir, a gear pump, Coriolis mass flowmeters, a pre-heater, the test section and a condenser, which is cooled with ambient air aided by two axial fans. Flow visualisation was conducted along the channel at the centre of the heat sink with a high-speed camera. The copper test section has fourty-four channels of width 0.36 mm, height 0.7 mm and length 20 mm, milled with a wall thickness of 0.1 mm on a 20 x 20 mm square area on the top of the block (D_h=475 μm). Five thermocouples were positioned along the channel at the centre of the block to help measure the local heat transfer coefficient at the dimensionless axial positions: z/L=0.17, 0.34, 0.5, 0.67 and 0.83 respectively. The heat flux was based on temperatures recorded by six thermocouples in the vertical direction. The inlet/outlet temperature and heat sink pressure drop are measured at the fluid line in the top plate as illustrated in Fig. 1. Inlet subcooling, ΔT_{sub}, is $T_{sat,p(i)} - T_{in}$, where $T_{sat,p(i)}$ is the fluid saturation temperature evaluated based on the inlet pressure and T_{in} is the inlet temperature. The single-phase length, L_{sub}, was obtained based on the iterative method detailed in [5]. The local heat transfer coefficient, $h_{(z)}$, is calculated as in Eq. 1, where $T_{f(z)}$ is the local fluid temperature, evaluated based on energy balance if in single-phase flow, [5]. In the flow boiling region, $T_{f(z)}$ is the saturation temperature evaluated at the local saturation pressure based on a linear pressure drop assumption. Additionally, $q_b^{"}$ is the base heat flux calculated from the vertical temperature gradient on the copper block and $T_{w(z)}$ is the temperature at the channel bottom wall. N, W, W_{ch}, H_{ch} and η are the heat sink width, channel width, channel height and fin efficiency respectively. The top plate was assumed to be adiabatic

$$h_{(z)} = \frac{q_b^{"}W}{(T_{w(z)}-T_{f(z)})*N(W_{ch}+2\eta H_{ch})} \tag{1}$$

The average heat transfer coefficient in this paper, $\bar{h}_{(z)}$, is averaged over the full channel length, covering both the single and two-phase region.

$$\bar{h}_{(z)} = \frac{1}{L}\int_0^L h_{(z)}\ dz \tag{2}$$

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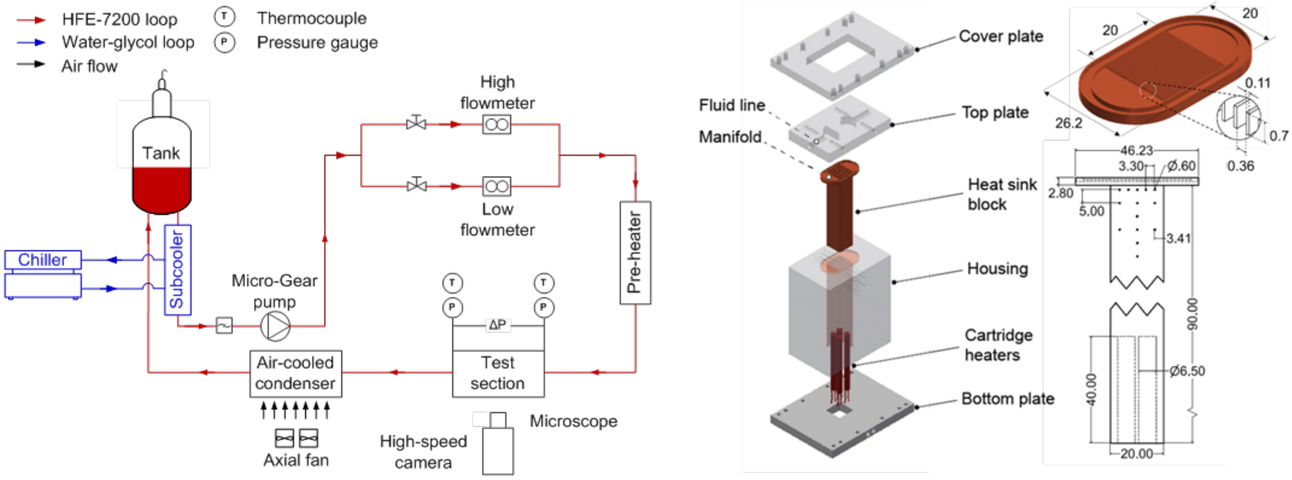

Fig. 1 Experimental facility and details of the microchannel test section.

3. RESULTS

Experiments were conducted at a mass flux of 200 kg/m^{2}s up to exit vapour qualities of 0.9 at a pressure of 1 bar (evaluated at the inlet). The saturation temperature of HFE-7200 at 1 bar is 75.05 °C. The effect of inlet subcooling was studied at 5 K, 10 K and 20 K for base heat fluxes in the range of 93 – 692 kW/m^2. Flow patterns including bubbly, slug, churn and annular flow were observed in this study. Flow visualisation showed several differences in the flow behaviour of nucleated bubbles at different inlet temperatures. At $q_b^{"}$ = 400 kW/m^2 and inlet subcooling of 5 K, bubbles nucleated from the channel side walls. As the bubbles grow and depart, they coalesce and form larger bubbles and slugs that quickly developed into churn flow near the channel inlet. At the same heat flux condition with 10 K subcooling, bubbles coalesced and formed slugs near the inlet, but only developed into churn flow further downstream. The bubbly flow regime was observed at the channel inlet at 20 K subcooling. Some bubbles departing from the side walls were observed to collapse and re-condense into the flow as they encounter the subcooled bulk fluid.

The single-phase length increased with increasing degree of subcooling and decreased with increasing heat flux. As expected, increasing inlet subcooling delayed the onset of saturated boiling in the channels at a given heat flux and mass flux condition. At $q_b^{"}$=400 kW/m^2, the single-phase length, L_{sub}, was 1.7 mm and 2.8 mm when ΔT_{sub}= 5 K and 10 K respectively. The onset of saturated boiling occurred very near the channel inlet (total channel length = 20 mm). As inlet subcooling is increased to 20 K, the single-phase region extended to 5.9 mm and saturated boiling was triggered further downstream. As mentioned above, departing bubbles near the channel inlet at 20 K subcooling were observed to re-condense into the subcooled fluid. The extended single-phase region, which typically exhibits a lower pressure drop compared to two-phase flow, and the differences in flow patterns observed, may have contributed to the lower total pressure drop measured across the heat sink at higher inlet subcooling conditions, see Fig. 2.

Average heat transfer along the channel also showed a notable dependence on inlet temperature, particularly at low heat fluxes ($q_b^{"}$ = 100 – 200 kW/m^2) and between inlet subcooling of 5 K and 20 K. Fig. 3 shows the average heat transfer coefficient (defined in Eq. 2) as a function of heat flux at different inlet temperatures. For a given heat flux, the average heat transfer coefficient is lower at a higher degree of inlet subcooling, especially at the lowest heat flux condition due to the considerable length of the single-phase region. In fact, at 20 K, the entire channel is in single-phase flow at $q_b^{"}$ = 100 kW/m^2 and the average heat transfer coefficient is < 2000 W/m^2 K. The heat transfer rates are much lower in the single-phase region and thus resulted in a lower average heat transfer coefficient. The effect of inlet subcooling on heat transfer performance appears to diminish as heat flux is increased. This could be due to the relatively shorter single-phase length at increasing heat fluxes. The low heat transfer coefficients characteristic of the single-phase region seem to have a weaker influence on the average heat transfer coefficient at moderate to high heat fluxes ($q_b^{"}$ > 300 kW/m^2). Flow pattern development along the channel, highly dependent upon the inlet subcooling degree for a given mass flux and heat flux condition, could also have had an effect on the slightly lower average heat transfer coefficients at moderate to high heat fluxes obtained at higher inlet subcooling conditions.

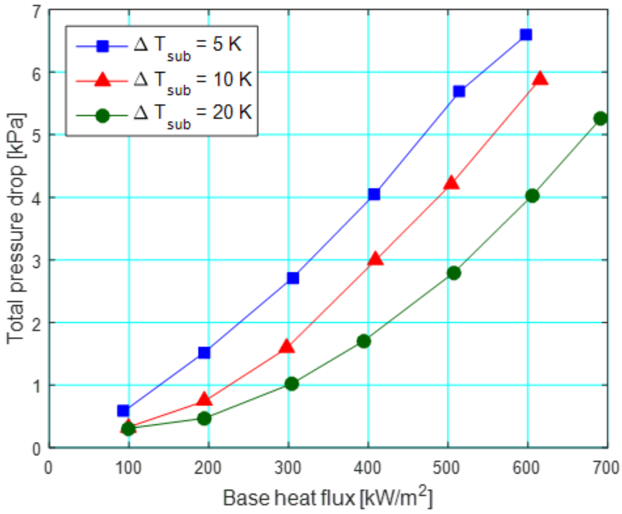

Fig. 2 Pressure drop across the heat sink as a function of base heat flux and degree of subcooling

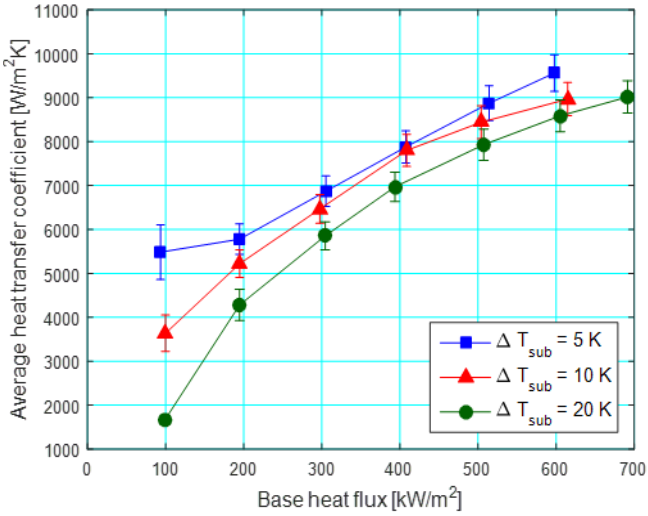

Fig. 3 Average heat transfer coefficient as a function of base heat flux and degree of subcooling.

4. CONCLUSIONS

Experiments were performed at G=200 kg/m^{2}s at a system pressure of 1 bar at three different inlet temperatures to assess the effect of inlet subcooling condition on the flow boiling heat transfer and pressure drop of refrigerant HFE-7200 in a microchannel heat sink. Flow patterns observed in the study were bubbly, slug, churn and annular flow. For a given heat flux and mass flux condition, increasing inlet subcooling extended the single-phase length in the channel. Increasing the applied heat flux reduced the single-phase length, affecting the pressure drop, average heat transfer coefficient and flow pattern development along the channel. The results indicated a notable dependence of pressure drop and heat transfer behaviour on inlet temperature across the range of heat fluxes studied (93 – 692 kW/m^2). Lower pressure drop values were recorded at higher inlet subcooling conditions due to the characteristically lower single-phase pressure loss and possibly also due to different flow patterns observed at each location in the channels. The average heat transfer coefficient decreased with increased subcooling, especially at low heat fluxes ($q_b^{"} < 300$ kW/m^2), due to the low heat transfer coefficients in the single-phase region. The effect of inlet subcooling weakened with increasing heat flux, possibly due to the decreasing single-phase length. The difference in flow pattern development could explain the slightly lower average heat transfer coefficients obtained at moderate to high heat fluxes with higher inlet subcooling degrees. The study verified the importance of the degree of subcooling when comparing heat transfer and pressure drop characteristics in microchannel heat sinks and when optimising the design of integrated thermal management systems for high heat flux electronic devices.

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