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Flow boiling of HFE-7100 in Multi-Microchannels: Aspect Ratio Effect

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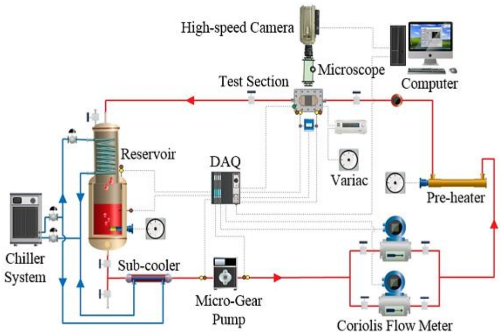
The effect of aspect ratio on the flow boiling heat transfer of HFE-7100 in horizontal multi-microchannels was studied. Three different channels with aspect ratios of 0.5, 1 and 2 were fabricated. These channels have the same hydraulic diameter, base area and average surface roughness. This study demonstrates that, the channel aspect ratio has a significant effect on the heat transfer results in the range studied.

1. Introduction

Channel aspect ratio could be considered an important parameter that affects the flow boiling characteristics, especially in micro scale configurations and was hence studied by a number of researchers, [1-5]. However, in some previous studies, the channel hydraulic diameter or channel surface roughness was not the same for all the channels, or the roughness value was not mentioned. Therefore, the present study aims to investigate this effect by keeping these variables constant. All experiments are set at a base heat flux of 21.732–531.216 kW/m^2, mass flux of 50–250 kg/m^2 s, system pressure of 1 bar and inlet sub-cooling of 5 K.

2. Experimental facility and data reduction

Figure 1 depicts the experimental facility, which consists of the test section, micro-gear pump, liquid reservoir, two Coriolis flow meters, sub-cooler, pre-heater, data logger and a Phantom high-speed camera coupled with a microscope. The test section consists of four main parts as shown in Figure 2. Both the bottom plate and housing were made of Polytetrafluoroethylene to reduce the heat loss. The cover plate was made of a transparent polycarbonate sheet to allow flow visualization. Oxygen-free copper was used to fabricate the heat sink block. Twelve K-type thermocouples were inserted in this block to measure the temperature distribution. Four cartridge heaters were inserted vertically from the bottom side.



Two T-type thermocouples were used to measure the fluid inlet/outlet temperatures. Two pressure transducers and one differential pressure transducer measure the inlet/outlet pressure and total pressure drop. All the heat sinks were manufactured using a high-precision milling machine, see Table 1 for dimensions.

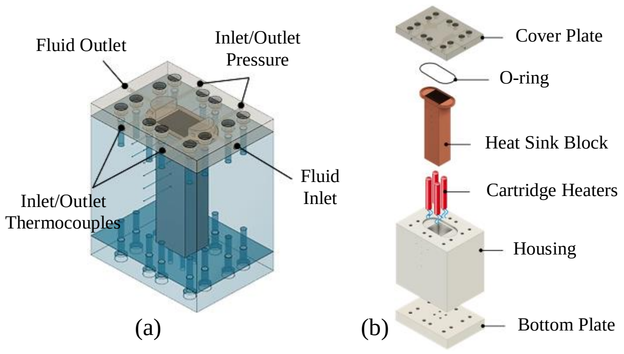


Figure 2. Test section (a) overall assembly (b) exploded drawing.

Table 1. Details of test sections.

Test section	H_{ch} [mm]	W_{ch} [mm]	W_{fin} [mm]	N [-]	D_h [mm]	β [-]	$W_b \times L_b$ [mm]	R_a [µm]
1	0.7	0.35	0.15	40	0.46	0.5	20×25	0.271
2	0.46	0.46	0.1	36	0.46	1	20×25	0.286
3	0.35	0.7	0.1	25	0.46	2	20×25	0.304

In the present study, the measured data was saved for two minutes then averaged after steady state was reached. The local two-phase heat transfer coefficient is calculated from the following equation:

$$h_{tp(z)} = \frac{q_b''*(W_{ch}+W_{fin})}{(T_{wi(z)}-T_{sat(z)})*(W_{ch}+2\eta*H_{ch})} \qquad (1)$$

The local saturation temperature $T_{sat(z)}$ was found from the local pressure in the two-phase region by assuming linear pressure drop.

3. Results and discussion

3.1 Flow patterns

Four flow patterns were captured for all heat sinks when the heat flux increased gradually, namely; bubbly, slug, churn and annular flow, see Figure 3. Bubbly flow occurred near the channel inlet and was characterized by numerous bubbles with different sizes. Both slug and churn flows were seen near the channel middle, while annular flow established near the channel outlet.

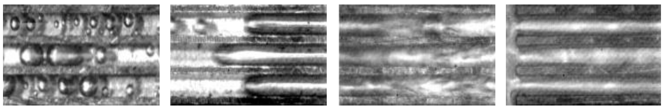

Bubbly (0.047) Slug (0.12) Churn (0.31) Annular (0.61)

Figure 3. Flow patterns at mass flux of 100 kg/m^2 s with corresponding vapour quality for a channel aspect ratio of 0.5.

It is worth mentioning that, at high heat fluxes, small nucleating bubbles were visualized in the liquid film of slug or annular flow, see also [6]. This could be due to the high wall superheat activating additional nucleation sites at high heat fluxes. Since the present study was carried out at low mass fluxes, flow reversal was found for all experiments. This mild flow reversal could be due to the rapid bubble generation at the channel inlet and slug formation, which expanded into both directions.

Figure 4 depicts the effect of channel aspect ratio on bubbly flow, near the inlet to the test section. It was found that, the bubble size in the channels with β = 2 is smaller than that observed for β = 0.5. However, this could be due to the larger vapour quality in the channels with β = 0.5 at corresponding locations and not only due to the aspect ratio effect. Moreover, the vapour slug length became longer when the channel width decreased, i.e. smaller aspect ratio.

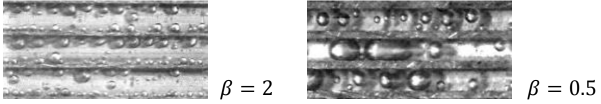


Figure 4. Effect of aspect ratio on the bubbly flow at mass flux of 100 kg/m^2 s and heat flux near 70 kW/m^2 (near channel inlet).

3.2 Heat transfer characteristics

The heat transfer coefficient was found to increase with increasing heat flux, while there is an insignificant effect of mass flux. This increase with increasing heat flux could be due to (i) an increase in the bubble generation frequency in the bubbly region at low heat flux, (ii) increased evaporation rate of the liquid film at low heat flux in the slug or annular region and (iii) in these two regions, an increased evaporation rate of the liquid film and nucleation in the liquid film at high heat flux.

The effect of channel aspect ratio on the local heat transfer coefficient at low and high heat fluxes is presented in Figure 5. This figure shows that, the local heat transfer coefficient increased with increasing aspect ratio.

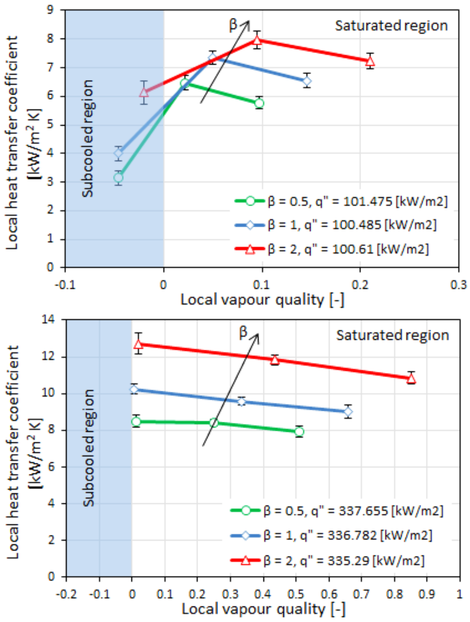


Figure 5. Channel aspect ratio effect at mass flux of 250 kg/m^2 s and different base heat fluxes.

At low quality when the flow was bubbly, this increase in heat transfer coefficient could be due to an increase in the bubble generation frequency. At moderate and high quality, when the flow patterns were slug, churn and annular, the enhancement in the heat transfer coefficient could be due to differences in the liquid film thickness at the channel sidewalls, as shown schematically in Figure 6, see similar figure in Fu et al. [5]. Our findings are only in partial agreement with Fu et al. [5]. They studied diverging channels of aspect ratio 0.16, 0.23, 0.4, 0.6, 1 and 1.2. Their square channel provided the highest heat transfer rate. They stated that in channels of aspect ratio other than 1, part of the walls was not wetted, which resulted in lower heat transfer rates. This included the channel of aspect ratio 1.2. In our case however, the heat transfer rate increased monotonically with aspect ratio from 0.5 to 2. One may argue that, in the deeper channel the liquid film collects at the lower half offering a higher thermal resistance and lower heat transfer rate. Similarly, the dry upper half of the channel results again in lower heat transfer rate. The physical phenomena and their effect on heat transfer rates in different aspect ratio channels requires further work using flow visualization at different orientations in at least partially transparent channels and heat transfer measurements.

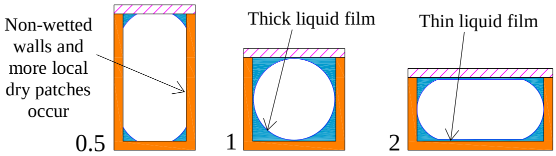


Figure 6. Schematic diagram of the liquid film thickness.

4. Conclusions

Flow boiling of HFE-7100 in microchannels was conducted at different operating conditions to study the aspect ratio effect. The following points can be summarized:

1. Bubbly, slug, churn and annular flow are obtained when the heat flux increases gradually. Some nucleating bubbles are seen in the liquid film of slug or annular flow.
2. Bubble size in the larger aspect ratio is smaller than that in smaller aspect ratio. The slug length becomes longer in the smaller aspect ratio.
3. Mild flow reversal is found in all experiments and heat sinks.
4. The heat transfer coefficient increases with heat flux, while there is insignificant effect of mass flux. Moreover, the local heat transfer coefficient is found to increase with aspect ratio.
5. The different flow and thermal behaviour of the channels with different aspect ratios needs further investigation.

Acknowledgements

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Nomenclature

D_h	Hydraulic diameter	Greek Symbols	
G	Mass flux	β	Aspect ratio, (W_{ch}/H_{ch})
H	Height	η	Fin efficiency
h_{tp}	Two-phase heat transfer coefficient	Subscripts	
L	Length	b	Base
N	Number of channels	ch	Channel
q''	Heat flux	fin	Channel fin
Ra	Surface average roughness	sat	Saturation
T	Temperature	wi	Internal wall surface
W	Width	z	Axial local

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