Proceedings of the 10th World Congress on Momentum, Heat and Mass Transfer (MHMT 2025)
Barcelona, Spain - April, 2025
Paper No. ENFHT 151
DOI: 10.11159/enfht25.151

Flow Boiling in Micro-Gap, Multi-Channels and Micro-Pin Fin Heat Exchangers

Ali H. Al-Zaidi[1], Mohamed M. Mahmoud[2], Atanas Ivanov[3], Tassos G. Karayiannis[3]
[1]University of Misan, Al-Amarah, Iraq
[2]Faculty of Engineering, Zagazig University, Zagazig, Egypt
[3]Department of Mechanical and Aerospace Engineering, Brunel University of London, UK,
tassos.karayiannis@brunel.ac.uk

***Abstract* -** The paper presents heat transfer and pressure drop results in three different micro-scale heat exchangers, namely: a micro-gap, multi-channels and micro-pin fin heat exchanger in flow boiling of HFE-7100. It was found that the micro-pin fin heat sink had better thermal performance than the other two geometries. The pressure drop in the micro-pin heat sink was higher than the other two designs. The flow instability was less severe in the micro gap and micro-pin fin geometries.

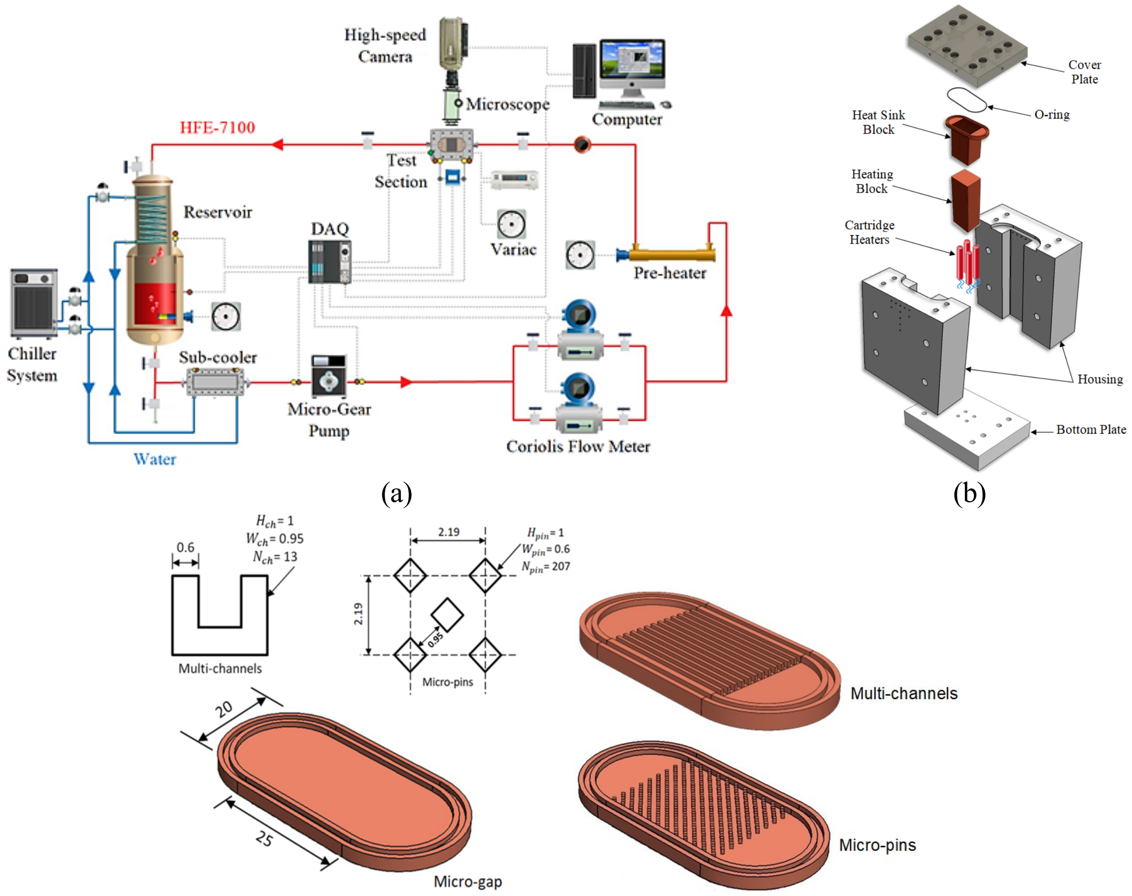
Keywords: flow boiling, micro-gap, micro-channels, micro-pin fins, electronics cooling.

1. Introduction

The demand for more efficient cooling systems for high heat flux devices increased in the last decade due to the continuous improvement in manufacturing processes and the subsequent development of more powerful and more compact electronics. The corresponding global thermal management market size was evaluated at USD 12.6 billion in 2022 and is projected to reach USD 32.83 billion by 2032 growing at a compound annual growth rate of 10% [1]. Different thermal management systems have been being developed and tested, and two-phase flow in micro-scale heat exchanger configurations is now considered one of the most promising cooling options. Different heat sink designs were proposed and examined in the literature such as rectangular multi-channels, wavy channels, expanding channels and pins [2]. However, further studies are still required to understand the two-phase flow phenomena and heat transfer and pressure drop characteristics in these micro-scales heat exchangers. The present study aims to experimentally investigate the thermal performance of three different heat sinks namely micro-gap, multi-channels and micro-pin fin using a dielectric and eco-friendly refrigerant at different operating conditions.

2. Experimental Facility

Fig. 1(a) shows the experimental facility used in this study that included two loops, the water-glycol cooling loop and the working fluid loop. HFE-7100 was tested as a working fluid at a wall heat flux up to 180 kW/m^2, mass flux of 100 kg/m^{2}s, system inlet pressure of 1 bar and inlet sub-cooling of 5 K. Fig. 1(b) shows the test section and the heat sink block. Three heat sinks, micro-gap, multi-channels and micro-pin fins, were made of oxygen-free copper using a micro-milling process. These heat sinks had the same heated base area of 20 mm × 25 mm and channel height of 1 mm, see Fig. 1(c). Both the multi-channels and the staggered diamond micro-pin fins were designed at the same channel hydraulic diameter, defined as $D_h = 2H_{ch}W_{ch}/H_{ch} + W_{ch}$. The width in the case of the micro-pin fins was 0.95 mm, same as the width of the channels, see figure 1 (c). This gave a hydraulic diameter of around 1 mm, and the same total heat transfer area of 0.0009 m^2 for both designs. The average roughness parameter of these heat sinks was found to be 0.1–0.15 μm. All the measuring sensors were carefully calibrated and the experimental rig was validated using adiabatic and diabatic experiments.



(c)

Fig. 1: Schematic diagram of (a) Experimental rig, [3] (b) Test section (c) Heat sinks (dimensions in mm).

The two-phase pressure drop ΔP_{tp} was calculated from Eq. (1).

$$\Delta P_{tp} = \Delta P_{meas} - (\Delta P_{sc} + \Delta P_{se}) - \Delta P_{sp} \quad (1)$$

where ΔP_{meas} is the measured total pressure drop, ΔP_{sc} is the sudden contraction pressure drop, ΔP_{se} is the sudden expansion and ΔP_{sp} is the single-phase pressure drop. The local heat transfer coefficient was calculated along the heated length, and then the average two-phase heat transfer coefficient, $\bar{h}_{tp}$, was found from Eq. (2).

$$\bar{h}_{tp} = \frac{1}{L_{tp}} \int_{L_{sub}}^{L_{ch}} h_{(z)} dz \quad (2)$$

In the above, L_{sub} is the length of the heat sink prior to the onset of boiling, L_{ch} is the total length (25 mm) and L_{tp} their difference. All other calculations used in this study are described in detail in [3]. The maximum uncertainty in the wall heat flux and the average two-phase heat transfer coefficient were found to be 12% and 15%, respectively.

3. Results and Discussion

The boiling curve of HFE-7100 for these three heats sinks at the center of the heat exchanger is shown in Fig. 2(a) where T_w is the wall temperature and T_{sat} the saturation temperature at the system pressure. Dryout regions and then the critical heat flux (CHF) occurred in both multi-channels and micro-gap due to the dry-spots on the surface. However, dryout regions were not observed in the micro-pin fins for the range studied. The wall temperature was also lower compared to the other two geometries. The good fluid mixing in the micro-pin heat sink could lead to re-wetting the surface and eliminates any dry-spots resulting in lower wall temperature. The average two-phase heat transfer coefficient was also higher, see Fig. 2(b).

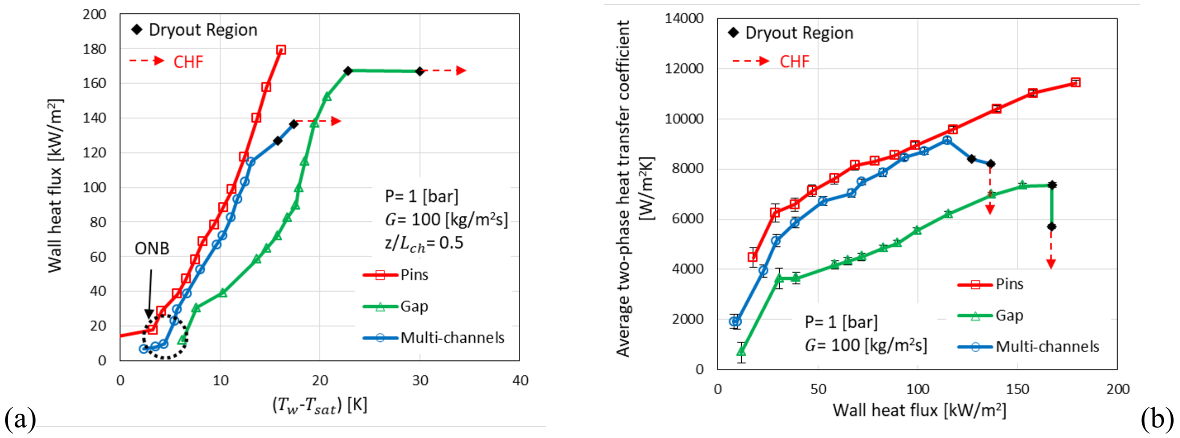


Fig. 2: Experimental results: (a) Boiling curve (b) Average two-phase heat transfer coefficient.

Fig. 3(a) shows that the micro-pin heat sink had a higher two-phase pressure drop as a result of the mixing process that occurs in this geometry (higher frictional pressure drop component). The system instability is presented in Fig. 3(b) using the data fluctuation of the measured pressure drop. Both the micro gap and the micro-pin heat sink had lower pressure fluctuation than that in the multi-channels. The slug expansion in both directions in the microchannels due to the confinement effect by the channel side-walls, as captured by the high-speed camera, could lead to this high fluctuation level [3].

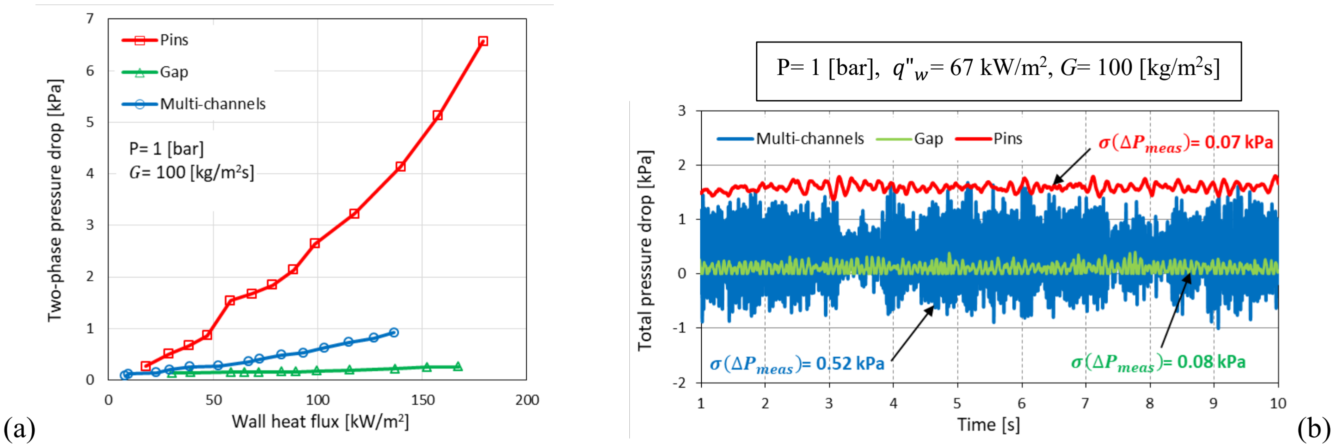


Fig. 3: Experimental results: (a) Two-phase pressure drop (b) Pressure drop fluctuation.

4. Conclusions

For the range studied, the micro-gap and the multi-channels heat sinks exhibited dryout regions and eventually CHF. This was not the case for the micro-pin fin heat exchanger, hence demonstrating higher possible heat dissipation rates. The micro-pin fins had lower wall temperature for a given load and higher average two-phase heat transfer coefficient compared to the other two geometries. The pressure drop in the micro-pin fin geometry was higher than both the micro-gap and the micro-channel heat sinks. The flow instabilities, assessed through pressure drop fluctuations, were lower in the micro-pin fin and micro-gap geometries.

Acknowledgments

The support of EPSRC through grant (EP/P004709/1) is acknowledged.

References

[1] Precedence Research (2024, July 8). Report code: 3449 (Energy and Power) [Online]. Available: https://www.precedenceresearch.com/thermal-management-market

[2] B. Hu, D. Qi, Y. Xu, M. Lin and Q.A. Wang, "Comparative Study of Flow Boiling Heat Transfer and Pressure Drop Characteristics in a Pin-Finned Heat Sink at Horizontal/Vertical Upward Flow Orientations", ASME Journal of Heat and Mass Transfer, vol. 146, no. 1–13, 2024.

[3] A.H. Al-Zaidi, M.M. Mahmoud and T.G. Karayiannis, "Flow Boiling of HFE-7100 in Microchannels: Experimental Study and Comparison with Correlations", IJHMT, vol. 140, no. 100–128. 2019.