Thermographical study of geometry and phase change influence on PDMS Microchannel liquid cooling devices

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Abstract. This work proposes a methodology in which high speed camera imaging is combined with infrared (IR) thermography to look at the effect of geometric parameters and boiling in the effectiveness of these coolers. PDMS microchannels were manufactured with 3 channel widths: 250, 500 and 750 µm. HFE7100 was used as the refrigerant. Pressure losses were significant for the thinnest geometry as clogging and flow reversal were observed. The dissipated heat flux, as measured by the IR camera was higher in the largest channels, due to the PDMS poor conductivity. Results obtained with HFE 7100 were then compared with those obtained with water at single-phase flow. For the same geometry, HFE 7100 resulted in a higher heat transfer coefficient than water.

1. Introduction

High Concentration Photovoltaic systems (HCPV) usually allow reducing cells area, by concentrating radiated energy through less expensive optical configurations. However, from the energetic point of view they have low efficiencies, as they dissipate very high heat loads, which are usually dispersed to the environment. PV cells conversion efficiency is known to decrease drastically as their temperature rises. In this context microchannel heat sinks can be an active cooling strategy. For defense applications, this kind of cooled panels can play a major role in operation scenarios, as it can be a clean an sustainable energy source, working under very harsh and demanding environments. On the other hand, the heat that is dissipated from the panels, can be reused in a secondary process, e.g. in sanitary waters. Microchannel heat exchangers were first proposed by [1]. Since then, progressively more complex analyses were performed to optimize every aspect of heat transfer in these coolers. For straight parallel channels, authors have investigated the influence of different geometrical parameters and determined their effectiveness as a balance between cooling and pressure losses. For instance, Upadhye and Kandlikar [2] in a numerical optimization work concluded that a cooler geometry with a higher number of smaller channels had a better performance when cooling an electronic chip. In an earlier study [3], the authors looked into the influence of the channel aspect ratio on thermal performance, through experimental and numerical work. Through testing several aspect ratios
it was concluded that it is preferable to implement an intermediate aspect ratio that allowed for greater heat removal, while minimizing pressure losses. Other channel shapes were tested in [4]. The authors of this work looked at channels with triangular, rectangular and trapezoidal sections. The authors concluded that increasing the number of channels decreased the thermal resistance but noted that the pressure drop increased. The common findings in these works lead to inevitably limiting how narrow the channels can be. Moreover, all the aforementioned studies used single-phase flow. Studies on multiphase flow have shown that boiling in microchannels is a highly unstable process, but with promising results. As early as 1996, Tran et al [5] explored boiling in 2.4mm rectangular and circular channels, observing mostly stable pressure and heat transfer improvements. Since then, the literature has reported increased heat transfer coefficients (HTC) for flow boiling in microchannels, but also focused on the instability of this type of cooler [6]. Clogging due to an elevated rate of nucleation and bubble size has been a concern in these studies as this instability has also been reported to influence the HTC. In this work, the proposed methodology looks into both the effect of geometric characteristics and phase change in microchannel cooling. Polydimethylsiloxane (PDMS) transparent microchannels with parallel rectangular channels will be used alongside with a visualization technique that combines high speed video and thermography with high temporal/spatial resolution. Main emphasis is given to increasing heat transfer while keeping the fluid flow stable and minimizing pressure losses.

2. Methodology

The PDMS prototypes were manufactured with 3D printed molds. The optical properties of the PDMS allow visualization of the bubbly flow. The prototypes carried different channel widths: 250µm, 500µm and 750µm, at a constant channel height of 1mm. The dimensions were chosen based on the printer extruder which is 250µm wide. The PDMS microchannel structure is placed on top of a stainless-steel (SST) AISI 304 surface, heated by applying a given current until it stabilizes at an initial temperature of 70 ºC. The SST foil is 20µm thick and is covered by a 5µm layer of black paint. The high emissivity (\(\epsilon = 0.95\)) allows that the heat exchange between the fluid-solid interface can be accurately accounted for. On the bottom of this structure is a sapphire window which allows a Xenics’s Onca MWIR high speed thermographic camera visual access. The camera is previously calibrated to account for the foil emissivity and sapphire transmissivity. At the inlet and outlet of the channels, pressure is measured with Wika A-10 pressure transmitters. A type K thermocouple is also used to measure the inlet fluid temperature. A syringe pump provides a constant flow of cooling fluid to the setup. The microchannels were tested at 5, 7, 10, 15 and 20 ml/min. The bubbly flow was observed using a Phantom v4.2 high-speed camera. The working fluid used is HFE7100 (with a saturation temperature of 61ºC), at an inlet temperature of 55 ºC, as measured by the thermocouple at \(T_{in}\). The results were later compared with water.

3. Results

The pressure losses measured during the tests can be seen in Figure 1 alongside with a picture of the bubbly flow in Figure 2. Previous studies observed that HFE 7100 bubbles can have a starting diameter of 400-1000 µm [7,8]. At the narrower geometry the bubbles clogged the channel which explains the increased pressure.

In Figure 3 shows infrared (IR) camera images as the surface cools down, once the fluid flow starts. The red stripes visible at 6s register the channels position, as the surface temperature drops faster in this region. In the later timestep, after the temperature stabilizes, the channels are no longer noticeable in the picture. It is worth noting that this difference is aggravated due to the poor thermal conductivity of the PDMS.

Figure 4 compares the dissipated heat flux between different geometries. This value was obtained by performing an energy balance at the liquid-solid interface with the temperature
data taken from the IR camera. The 250 µm channel shows the worse performance, and the 500 µm channel shows unstable but better results. It can be concluded that there is a relation between bubble diameter and channel width, that influences the performance of the cooling devices. In line with this, one should favor widths that do not surpass bubble diameters during boiling to avoid clogging effects in order to take advantage of latent heat dissipation without high pressure losses.

A comparison between single and multiphase flow was made, using the 500µm channel width geometry. Figure 5 depicts the relationship between heat transfer coefficient and flow rate for both cases. Higher heat transfer coefficients were obtained for the multiphase when compared to the single-phase flow for the same conditions. These results evidence that latent heat removal by boiling improved the overall heat transfer coefficient. Due to the worse thermal properties of HFE7100 it is also possible to state that, in the multiphase flow scenario, latent heat removal plays a paramount role in heat transfer. In the single-phase flow heat is transferred to the fluid largely through forced convection. The uncertainty of the results is the product of the highly unstable boiling process.
4. Conclusions
In conclusion, by combining thermography and high speed images it was possible to analyse the progressive cooling of the channels, and how it varied between the wall and liquid regions. Additionally multiphase flow shows promising results, having a higher heat transfer coefficient than water. But pressure loss on the microchannel devices limits the dimensions of the channels before clogging affects the flow. Smaller devices could not be produced by the current methodology, but in future work the trade-off between clogging pressure increase and heat transfer enhancement should be investigated.

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