Enhanced Pool Boiling With Ethanol at Subatmospheric Pressures for Electronics Cooling

The growing trend in miniaturization of electronics has generated a need for efficient thermal management of these devices. Boiling has the ability to dissipate a high heat flux while maintaining a small temperature difference. A vapor chamber with pool boiling offers an effective way to provide cooling and to maintain temperature uniformity. The objective of the current work is to investigate pool boiling performance of ethanol on enhanced microchannel surfaces. Ethanol is an attractive working fluid due to its lower normal boiling point compared to water. The saturation temperature of ethanol offers an effective way to provide cooling and to maintain uniformity. The overall thermal performance of these liquids is still considerably lower than that for a plain surface with water.

Keywords: pool boiling, heat transfer enhancement, open microchannels, critical heat flux, subatmospheric pressure

Introduction

Cooling with phase change is an attractive option for heat dissipation in high power electronic systems. Over the past three decades, researchers have investigated different passive enhancement techniques to increase the heat transfer coefficient and the critical heat flux (CHF). They have used different working fluids, e.g., water, refrigerants, alcohols, binary mixture, and more recently nanofluids in pool boiling systems. Lowering the system pressure to maintain a low boiling surface temperature has also been explored with water in particular. The performance of a pool boiling system is characterized by the pool boiling curve depicting heat flux versus wall superheat, and the critical heat flux. The heat transfer coefficient is readily obtained from the boiling curve.

Water with its known properties, availability, and nontoxic nature has been widely used by researchers for augmenting pool boiling heat transfer. McGillis and Carey [1] conducted experiments with a 12.7 mm × 12.7 mm horizontal surface with rectangular fins at 4 kPa and 9 kPa using water. They concluded that at low pressures, the boiling performance significantly decreased but the surface temperature under pool boiling was well within the acceptable range for electronics cooling. Pal and Joshi [2] used a copper block with an array of cross-cut rectangular channels as their enhanced structure. At subatmospheric pressure, they obtained a maximum heat flux of 1.11 MW/m² (111 W/cm²) at 83 °C surface temperature. Cooke and Kandlikar [3] used open microchannels on a copper chip in water at atmospheric pressure. They obtained heat fluxes of 2.44 MW/m² (244 W/cm²) for a wall superheat of less than 10 °C. Different enhancement structures such as microporous coatings [4,5], re-entrant cavities [6], nanostructures [7,8] and finned surfaces [9] have been investigated with water as the working fluid at different pressures to obtain high heat flux cooling. High vacuum (lower than 10 kPa pressure) is required with water as the working fluid to attain desired low temperatures suitable in the electronics cooling application.

The Fluoroint series by 3M has garnered a lot of attention due to their desirable properties for electronics cooling. Mudawar and Anderson [10] used FC-72 and FC-87 at atmospheric pressures with various enhancement structures. Heat fluxes in excess of 1 MW/m² (100 W/cm²) with saturated FC-72 were recorded for cylindrical enhanced surfaces. Rainey et al. [11] conducted experiments with microporous square pin-finned structures using FC-72 over a subcooling range of 0 °C–50 °C and a pressure range of 30 kPa–150 kPa. They observed that the boiling performance improved with increasing pressure, and the CHF increased with subcooling. Similar to water, different enhancement techniques [12–16] have been studied to maximize heat transfer using Fluoroint liquids. In spite of the enhancement techniques employed, the overall thermal performance of these liquids is still considerably lower than that for a plain surface with water.

Alcohols and aqueous mixtures have also been investigated to combine the advantages of water (excellent thermal performance) and alcohols (lower saturation temperature). Nishikawa et al. [17] studied nucleate boiling of saturated water and ethanol on a horizontal smooth copper surface. They observed intermittent boiling in the low heat flux region at low pressures without any steady nucleation sites. McGillis et al. [18] investigated the boiling behavior of water/methanol and water/two-propanol at subatmospheric and atmospheric pressures. They reported that small addition of alcohol to water helped in increasing CHF above that of pure water. Sakashita et al. [19] tested saturated mixtures of two-propanol/water on a 12-mm diameter disk at atmospheric pressure. They reported an increase in CHF of up to 1.7 times...
compared to that with water. Bailey et al. [20] used three fluids, pentane, methanol, and water in different temperature ranges. Pentane performed the best with a heat flux of 45 W/cm² for a surface temperature below 80 °C. Warrier et al. [21] tested mixtures of HFE 7200 with methanol and ethoxybutane to identify a suitable fluid candidate for electronics cooling. The authors concluded that both mixtures showed an increase in the CHF. However, the HFE 7200 + ethoxybutane mixtures were suggested as viable candidates since methanol had a detrimental effect on the incipience superheat. Pastuszko [22] recently investigated narrow tunnel structures (NTSs) in water, ethanol and R-123 at atmospheric pressure. The NTSs consisted of surface extensions, perforated foils and subsurface narrow tunnels. For ethanol, a maximum heat flux of 300 kW/m² at 20 °C wall superheat was obtained. Flammability and low toxicity are the two biggest drawbacks of ethanol as the working fluid for electronics cooling. However, ethanol can be used in a completely sealed vapor chamber to address the above drawbacks.

As seen from the literature, surface enhancements allow high heat transfer rates to be obtained at low wall superheats. The objective of the present study was to explore open microchannels as enhanced surfaces with ethanol at subatmospheric pressures for meeting the heat flux and wall temperature limits in electronics cooling.

Experimental Setup

A test setup, shown in Fig. 1, was designed and fabricated to test pool boiling performance with ethanol and other fluids at subatmospheric pressures. It consisted of a stainless steel cylindrical chamber of 100 mm diameter to hold the working fluid over a heated chip surface and a condenser unit. The stainless steel chamber had two cylindrical flanges which were sealed with four C-clamps for easy re-assembly during test section changeover. Multiple O-rings were used to ensure that the test setup remained both leak-proof and subatmospheric pressure testing could be done. Openings were provided on the top flange for ethanol inlet, vacuum port, thermocouple probe, and inlet and outlet connections for the condenser. A coiled copper tube acted as a condenser inside the chamber. The condenser was connected to a constant temperature circulating water bath, which provided heating. A 120-VDC, 200-W auxiliary heater was installed through an opening in the bottom flange. It was used to maintain the ethanol at the desired saturation temperature by continuously boiling the liquid. A Garolite chip holder was fabricated to hold the copper test section on the bottom flange by threaded bolts. Garolite was used because of its lower thermal conductivity (0.27 W/m °C) and ability to withstand high temperatures (168 °C). A 15-mm square opening was made in the bottom of the chip holder for the heater assembly to contact the test section with a thin layer of thermally conducting paste in between the two contacting surfaces.

A 120-VDC, 450-W capacity cartridge heater was fitted into a copper rod to provide heat flux to the test chips as shown in Fig. 2. The copper chip was machined to have a 10 mm × 10 mm top surface with a 2 mm × 2 mm machined groove beneath the heated area on the underside of the test section. This was done to promote onedimensional heat transfer from the copper rod to the test section surface. Additionally, the copper rod was wrapped in a high temperature ceramic insulating sleeve to reduce heat losses. Three K-type thermocouples spaced 8 mm apart on the copper block were used to measure the temperature gradient, which was then used to calculate the heat flux.

The heat flux to the test section was calculated using 1D conduction equation

$$q'' = -k_c \frac{dT}{dx}$$  \hspace{1cm} (1)

where the temperature gradient dT/dx was calculated using the three-point backward Taylor’s series approximation

$$\frac{dT}{dx} = \frac{3T_1 - 4T_2 + T_3}{2\Delta x}$$  \hspace{1cm} (2)

The Garolite base held the copper rod and the cartridge heater in place. A National Instruments cDaq-9172 data acquisition system with NI-9213 temperature module was used to record the temperature. A LabVIEW® virtual instrument displayed and calculated the surface temperature and heat flux.

Test Section

The test section used in the study was a 20 mm × 20 mm × 3 mm flat copper chip as shown in the Fig. 3. On the heater side it has a 10 mm × 10 mm × 2 mm groove all around to reduce the heat losses similar to the plain copper chip as described earlier. A 700 μm hole was drilled on the side of the chip to reach the chip center. A fourth K-type thermocouple was inserted from the underside of the chip in this hole for the direct measurement of the chip temperature. The wall temperature at the top of the boiling surface was calculated using the heat flux obtained from Eq. (1) and is given by

![Fig. 1 Schematic of the pool boiling test setup](image1)
![Fig. 2 Schematic of the heater assembly](image2)
depth and channel width on the boiling performance at different pressures. The focus of the current work is to investigate the effects of channel geometry on the boiling performance at different saturation pressures. Microchannel geometry was selected as the enhanced structure due to its high performance with water reported in literature [3]. Microchannels were machined over a central area of the 10 mm × 10 mm surface on the boiling side of the chip using a computer numerical control (CNC) mill. The dimensions of the machined microchannels were measured using a confocal laser scanning microscope to ensure accuracy and are given in Table 1. Average roughness values obtained using the microscope were: 2.9 μm for the plain surface—2.8 μm for the microchannel surface—2.9 μm, and bottom surface of the microchannel—2.5 μm. The focus of the current work is to investigate the effects of channel depth and channel width on the boiling performance at different saturation pressures.

Uncertainty Analysis

An uncertainty analysis was conducted similar to that presented in Ref. [3,23] for a similar experimental setup. The largest factor for uncertainty was observed in the thermocouple measurement. Therefore, all thermocouples were individually calibrated using a thermocouple calibrator at five different temperature points. An uncertainty of 0.1 °C was determined for temperature measurement taking into consideration the calibration accuracy, precision, and random errors. Uncertainties in heat flux and surface temperature were calculated through error propagation analysis. At low heat fluxes, 7% uncertainty was estimated in the heat flux and 0.2 °C in wall superheat. At higher heat fluxes, the uncertainty in the heat flux measurement was reduced to 4%.

Experimental Procedure

Testing was done to check for leaks by reducing the system pressure to 10 kPa and monitoring it over a 24-h period. The system was charged with ethanol via the vacuum port to the desired pressure. After the vacuum port valve was closed, the ethanol inlet valve was opened to allow liquid to enter into the chamber. Ethanol level in the boiling chamber was adjusted to 50 mm above the heater surface. The auxiliary heater and the cartridge heater were powered by two independent power supplies. Thermal paste was applied on the tip of the copper heater block to reduce the contact resistance with the copper chip. A very low contact resistance was obtained; however, it was not relevant as the actual chip temperature was also measured by a fourth thermocouple, \( T_{c} \), directly under the boiling surface. The contact resistance value was back calculated and found to be approximately \( 8 \times 10^{-6} \text{ m}^2\text{C/W} \).

The pressure was increased in a stepwise fashion once the liquid in the system reached the desired saturation temperature. Readings were recorded at each step after the system reached steady state when the thermocouples did not fluctuate by greater than ±0.1 °C over a period of 10 min.

The pressure inside the closed chamber was maintained at atmospheric level through the use of the condenser by adjusting the temperature and flow rate of the cooling water from the constant temperature water bath and the power supplied to the auxiliary heater. The condensing temperature was lowered to achieve a lower saturation temperature in the chamber for low pressure testing.

Results

Initially, pool boiling experiments were conducted with ethanol and FC-87 over a plain chip to compare the relative performance of these two fluids. Further testing was carried out with ethanol over a range of saturation temperatures. The four microchannel chips described in Table 1 were experimentally investigated to study the effect of geometrical parameters on the heat transfer performance at these pressures.

Two important parameters in the cooling system design for electronics are the maximum heat flux dissipated at the surface and the highest wall temperature, which is limited by the allowable junction temperature of the electronic device. These parameters are addressed in this section. The heat transfer performance results are presented in the form of boiling curves showing the heat flux as a function of the wall superheat. The heat flux was calculated using the projected area of the heater surface (which was 100 mm² for all chips tested). The wall superheat was defined as the difference between the wall temperature of the surface exposed to the liquid and the saturation temperature. The wall temperature for the current study was calculated as the temperature at the top surface of each microchannel chip. The experiments were stopped as soon as there were indications of the imminent CHF as indicated by the instantaneous chip surface temperature. The previous steady-state reading was reported as the CHF value.

Table 2 shows the four different saturation pressures and corresponding saturation temperatures employed during testing. A lower saturation temperature is desirable for removing heat effectively from the chip, but the corresponding saturation pressure decreased considerably. The testing was aimed at identifying the combined effect of lower saturation temperature and corresponding heat transfer performance.

Comparison of Ethanol and FC-87. Plain surface chips were tested at atmospheric pressure to compare the performance of ethanol and FC-87 as working fluids. Figure 4 shows the respective boiling curves on a plain surface chip. Boiling performance for both fluids was similar at lower heat fluxes prior to the onset of nucleation. Both fluids exhibited boiling temperature overshoot, which was much more prominent with ethanol.

<table>
<thead>
<tr>
<th>Chip no.</th>
<th>Type</th>
<th>Channel depth (μm)</th>
<th>Channel width (μm)</th>
<th>Fin width (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>Plain</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>Microchannel</td>
<td>456</td>
<td>207</td>
<td>193</td>
</tr>
<tr>
<td>2</td>
<td>Microchannel</td>
<td>470</td>
<td>194</td>
<td>402</td>
</tr>
<tr>
<td>3</td>
<td>Microchannel</td>
<td>410</td>
<td>406</td>
<td>195</td>
</tr>
<tr>
<td>4</td>
<td>Microchannel</td>
<td>245</td>
<td>396</td>
<td>200</td>
</tr>
</tbody>
</table>

where \( T_{wall} = T_{c} - q'' \left( \frac{x_1}{k_{Cu}} \right) \) (3)

Table 1 Geometrical details of the copper chips tested

Table 2 System pressure and corresponding saturation temperatures for ethanol employed in the experiments

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>101.3</th>
<th>66.7</th>
<th>33.3</th>
<th>16.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation temperature (°C)</td>
<td>78.3</td>
<td>68.3</td>
<td>52.5</td>
<td>38.2</td>
</tr>
</tbody>
</table>
Microchannel Surface Testing at Different Pressures. The boiling performance plots for the four microchannel copper chips, chips 1–4 listed in Table 1, at four different pressures are shown in Figs. 6(a)–6(d). Boiling overshoot was observed in all microchannel chips tested. At low heat fluxes, below 100 kW/m², boiling curves were quite similar for all chips under all four pressure conditions. This was reasonable as the chip performance was quite low under the natural convection conditions, and small differences among the performance could not be clearly seen on the plot.

For chip 1 shown in Fig. 6(a), a maximum heat flux of 1.1 MW/m² was noted at atmospheric pressure with a wall superheat of 17°C with ethanol. After onset of nucleate boiling (ONB), a linear increase in heat flux with wall superheat was observed. At lower pressures, as seen with the plain surface chip, pool boiling performance decreased correspondingly. For chip 2, a maximum heat flux of 1.14 MW/m² at 20°C wall superheat was recorded as shown in Fig. 6(b). At 101.3 kPa and 66.7 kPa, the boiling curves followed an almost vertical trajectory for chip 2, while at lower pressures, heat flux increased linearly with the wall superheat. Chips 3 and 4 showed a similar linearly increasing boiling curve as that for chip 1 at all pressures. The boiling performance also decreased with a reduction in pressure similar to that of a plain surface chip. This behavior was consistent with the trends observed in literature [1,2,9,11] for low pressure testing.

Figure 7 shows the corresponding heat transfer coefficients plotted against the wall superheat comparing different microchannel chips with the plain chip at atmospheric pressure. Thermal performance of a surface can also be compared through the heat transfer coefficient values. As expected, all microchannel surfaces performed better than the plain surface. Data points for all tested chips below around 5 kW/m²°C represented values before the ONB. The higher values for superheats between 0 and 5°C reflect the single-phase heat transfer as described in Ref. [24]. Chip 1 performed the best with a heat transfer coefficient of 65 kW/m²°C amongst the microchannel chips tested.

Discussion

All tested chips followed a similar boiling curve pattern with natural convection heat transfer initially at lower heat fluxes. After the onset of nucleate boiling, the surface temperature increased and more nucleation sites were activated causing more heat to be dissipated. The experiments were stopped when the maximum wall superheat started to increase rapidly, approximately at a wall superheat of 20°C for atmospheric pressure testing. For low pressure testing a surface temperature of 85°C was set as the upper bound.

Effect of Channel Width. Comparing the geometrical parameters listed in Table 1, chips 1 and 3 had identical geometrical parameters except for the channel width. Figure 8 shows heat transfer coefficient against wall superheat plot for these chips at 101.3 kPa and 66.7 kPa. Chip 1 with narrow channels (207 μm) showed superior performance compared to the wider channels (406 μm) of chip 3. Data for only two system pressures were shown in the plot to avoid overcrowding of data points. Narrow channels performed better at all four pressures. Chip 2 also performed better than chip 3 due to the effect of narrow channel width. McGills and Carey [1] also observed small fin gaps to be more effective at low pressures for water.

Effect of Channel Depth. In general, deeper channels (>400 μm) showed better pool boiling performance than...
shallower channels (200 μm). As seen in Fig. 7, chip 4 showed the lowest performance of all the microchannel chips due to its smallest depth and wide channels. Chips 3 and 4 have different depths but similar channel and fin widths. The maximum heat flux dissipated by chip 4 is 710 kW/m² as seen in Fig. 6(d) while chip 3 dissipated significantly higher heat flux of 1.1 MW/m². Chips 1 and 2 have an overall superior performance to chip 3 even though they have similar depths. This is due to the narrow channel widths of chips 1 and 2 compared to the wider channel width of chip 3.

Chips 1 and 2 have similar channel widths and depths but different fin widths. Chip 1 with a narrow fin width (193 μm) performs better than chip 2 with wider width (407 μm) as shown in Fig. 7. The total number of channels present on chip 2 in the fixed 10 mm × 10 mm area is less than chip 1 due to the wider fin width. The overall difference between the performances of the chips is reduced considerably at low pressures. Fin width has a small effect on overall boiling performance compared to channel width and channel depth.

**Effect of Pressure.** It is well established that the pool boiling performance deteriorates with a decrease in pressure as seen from the literature review. Figure 6 shows the effect of pressure for different chips, the boiling curve shifts toward right causing the wall superheat to increase at a given heat flux. This in turn increases the surface temperature with increasing heat flux. However, the saturation temperature decreases with a reduction in pressure. The combined effect of these factors is more relevant as the actual wall temperature is of greater interest in electronics cooling than simply the wall superheat value.

Table 3 shows various maximum heat fluxes and wall temperatures (in bold) obtained for the plain and four microchannel chips at four different pressures. At lower pressures, saturation temperature

![Fig. 6 Boiling curves of microchannel enhanced surfaces chip for ethanol at different pressures: (a) chip 1, (b) chip 2, (c) chip 3, and (d) chip 4](image)

![Fig. 7 Heat transfer coefficients for the tested chips at atmospheric pressure](image)

![Fig. 8 Heat transfer coefficients for chips 1 and 3 at 101.3 kPa and 66.7 kPa](image)
temperature to decrease at a given wall superheat. As seen from the chip surface temperature. A limiting temperature of 85°C four pressures for chip 1. The heat flux is plotted as a function of temperature as the limiting criterion.

in the thermal path encountered while using the actual junction with ethanol at a pressure of 33.3 kPa. Further refinements to the has the highest heat dissipation rate among all chips tested. (shown as underlined values) for all microchannel chips. Chip 1

seen that heat flux dissipation of over 900 kW/m² is achieved with set as the upper limit for safe operation of the actual IC chip. It is

conclusions are drawn based on the experimental results.

Conclusions
A pool boiling performance study with ethanol as a working fluid was conducted to investigate the effects of enhanced surfaces at atmospheric and subatmospheric pressures. The following conclusions are drawn based on the experimental results.

(a) Temperature overshoot was observed on all chips tested. It was due to the inherent wetting nature of ethanol. Specific measures should be taken to avoid this overshoot in a practical system.

(b) Microchannel enhanced surfaces were able to dissipate more than twice the amount of heat flux as the plain surface at a given wall superheat in the nucleate boiling region.

(c) Effect of the geometrical parameters was studied. The highest performing chip had deeper (400 μm) and narrower channels (200 μm). Fin width did not have any significant effect compared to channel width and depth.

(d) Effect of pressure was seen to be in agreement with the reported literature. Pool boiling performance deteriorated with decrease in system pressure. Surface temperatures of all chips were reduced with a decrease in pressure, indicating a stronger effect due to the reduction in the corresponding saturation temperature of the liquid.

(e) Chip 1 with a channel width of 207 μm, channel depth of 456 μm and fin width of 193 μm performed the best among the group.

(f) A maximum heat flux 904 kW/m² was obtained for chip 1 while maintaining the surface temperature at 84.1°C with ethanol at a system pressure of 33.3 kPa.

The current study provides a better understanding of the pool boiling performance of microchannel surfaces with ethanol at sub-atmospheric pressures. A heat flux of 900 kW/m² was dissipated with the enhanced surface while maintaining the wall temperature below 85°C with ethanol as the working fluid at a subatmospheric pressure. Further safety analysis and overshoot concerns need to be addressed before ethanol at these conditions is deployed in practical chip cooling applications.

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Nomenclature

\[ q'' = \text{max heat flux, W/m}^2 \]

\[ x = \text{distance, m} \]

\[ T_{sat} = \text{saturation temperature, °C} \]

\[ T_e = \text{measured chip temperature, °C} \]

\[ T_{wall} = \text{wall temperature, °C} \]

\[ h = \text{heat transfer coefficient, W/m}^2\cdot\text{°C} \]

Greek Symbols

\[ \Delta T_{sw} = \text{wall superheat, °C} \]

\[ \Delta x = \text{distance between thermocouples, m} \]

References


