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HIGH HEAT FLUX SUBCOOLED FLOW BOILING OF METHANOL IN MICROTUBES

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ABSTRACT

As the proper cooling of the electronic devices leads to significant increase in the performance, two-phase heat transfer to dielectric liquids can be of an interest especially for thermal management solutions for high power density devices with extremely high heat fluxes. In this paper, the pressure drop and critical heat flux (CHF) for subcooled flow boiling of methanol at high heat fluxes exceeding 1 kW/cm^2 is investigated. Methanol was propelled into microtubes ($ID = 265$ and $150 \text{ }\mu\text{m}$) at flow rates up to 40 ml/min (mass fluxes approaching $10000 \text{ kg/m}^2\text{-s}$), boiled in a portion of the microtube by passing DC current through the walls, and the two-phase pressure drop and CHF were measured for a range of operating parameters. The two-phase pressure drop for subcooled flow boiling was found to be significantly lower than the saturated flow boiling case, which can lead to lower pumping powers and more stability in the cooling systems. CHF was found to be increasing almost linearly with Re and inverse of inner diameter ($1/ID$), while for a given inner diameter, it decreases with increasing heated length.

INTRODUCTION

Proper thermal management of high power density electronic systems, such as, GaN-based RF power amplifiers and

embedded high performance computing modules, can lead to significant improvements in performance metrics and system reliability. The best thermal performance will require the development of highly optimized microfluidic heat exchangers that target spatially-averaged heat fluxes exceeding 1 kW/cm^2 with local maxima exceeding 30 kW/cm^2 at hotspots. A promising candidate approach is subcooled flow boiling in a microfluidic heat exchanger, which allows simultaneous minimization of convective resistances and a significant increase in the cooling capacity at a given mass flow rate. This approach can particularly improve the cooling performance if it is integrated at chip level, which in turn, requires use of dielectric working fluids. While two-phase flow in microtubes has received much attention in the literature, there remains a gap for the specific case of wall heat fluxes approaching 1 kW/cm^2 for fluids other than water.

Subcooled boiling, have been extensively investigated in the past. Researchers have studied CHF [1–3], onset of boiling [4,5], and heat transfer coefficient and pressure drop [6,7] in a vast range of flow rates and fluids for subcooled flow boiling. For saturated flow boiling, the available literature is even more extensive ([8–13] to name a few), and researchers have managed to develop analytical solutions especially for convective flow boiling (e.g., [8]) to predict the two-phase flow behavior. However, the available data for predicting the thermofluidic and

limiting wall heat fluxes (CHF), at target heat fluxes exceeding 1 kW/cm^2 (which requires large mass fluxes, and microscale hydraulic diameters), in particular for dielectric liquids is limited.

This paper presents the experimental results of two-phase pressure drop and critical heat flux (CHF) for subcooled flow boiling of methanol in stainless steel microtubes (inner diameter of $265 \text{ }\mu\text{m}$ and $150 \text{ }\mu\text{m}$) with wall heat fluxes surpassing 1 kW/cm^2 . Subcooled methanol is delivered to microtubes ($\sim 30 \text{ mm}$ long) at mass fluxes (G) up to $10000 \text{ kg/m}^2\text{-s}$ while a portion of the microtube is uniformly heated to boil the methanol. The induced two-phase pressure drops as well as limiting heat fluxes (CHF) are measured and the effect of different parameters were studied. High mechanical and temperature tolerability of stainless steel, combined with its electrical conductivity (heater element) enabled us to conduct thermofluidic tests at extremely high heat fluxes (up to $\sim 1 \text{ kW/cm}^2$) and high mass fluxes (approaching $10,000 \text{ kg/m}^2\text{-s}$). Furthermore, testing a single-channel flow helped eliminating the extra corrections required for flow boiling (especially for CHF) in micro-fabricated devices, such as fin efficiency analysis and two-phase parallel channel instabilities. The data obtained for pressure drop and critical heat flux, at these heat and mass flow rates, and the trend of these parameters with respect to heat and mass fluxes, can expand the available database and help improve the existing correlations for proper design of effective heat exchangers for extremely high heat fluxes using dielectric liquids.

EXPERIMENTAL SETUP AND METHOD

Selection of the fluid

A critical element affecting the performance of any heat sink is the selection of the working fluid to meet the stringent thermofluidic requirements and operational constraints and limitations. The intrachip cooling solutions require the use of dielectric liquids, which have inferior thermal properties compared to water, especially for two phase boiling heat transfer. The thermal conductivity (k_l) of most refrigerants and coolants are less than 20% of water, specific heats (C_p) are less than 30%,

and the latent heat of evaporation (h_{fg}) is almost one order of magnitude lower than water. Considering the high heat flux and COP requirements for the next generation of thermal management solutions, methanol was selected as the working fluid due to its higher values of thermal conductivity and latent heat of evaporation compared to other dielectric liquids (Table 1). These properties can lead to high heat transfer coefficients and lower pumping powers for the developing heat exchangers.

Table 1 Thermophysical properties of selected fluids at room condition (temperature and/or pressure)

Fluid	Freezing/Boiling Temperatures (°C)	k_l (W/m-K)	C_p (kJ/kg-K)	h_{fg} (kJ/kg)
Water	0 / 100	600×10^{-3}	4.2	2200
Methanol	-97.6 / 64.7	200×10^{-3}	2.4	1180
R245fa	-106.7 / 15.2	86×10^{-3}	0.33	187

Experimental apparatus and procedure

A schematic of the experimental set up is presented in Fig 1. Methanol is propelled to the open loop liquid delivery line by a syringe pump (constant displacement) in order to maintain the constant flow rate while compensating for the increased pressure drop (due to phase-change) and avoid Ledinegg instabilities [14]. The microtubes are commercially-available stainless steel blunt needles ($ID = 150 \text{ }\mu\text{m}$ and $265 \text{ }\mu\text{m}$) and were connected to the liquid loop through luer-lock connections. A short length of the microtube midway to the outlet was heated up by passing electrical current through the microtube wall to boil the methanol (Fig 2). The exhaust flow was collected in a container for proper recycling/disposal, while the outlet temperature downstream of the microtube was measured by a thermocouple.

Two wires from a high current DC power supply were soldered to the stainless steel microtube to deliver power. Electrical current was passed through the microtube wall (with wall thickness of $80 \text{ }\mu\text{m}$ and $92 \text{ }\mu\text{m}$ for $ID=150 \text{ }\mu\text{m}$ and $ID=265 \text{ }\mu\text{m}$ microtubes respectively) between the connections, and heated up the test section. Since the electrical resistances of the

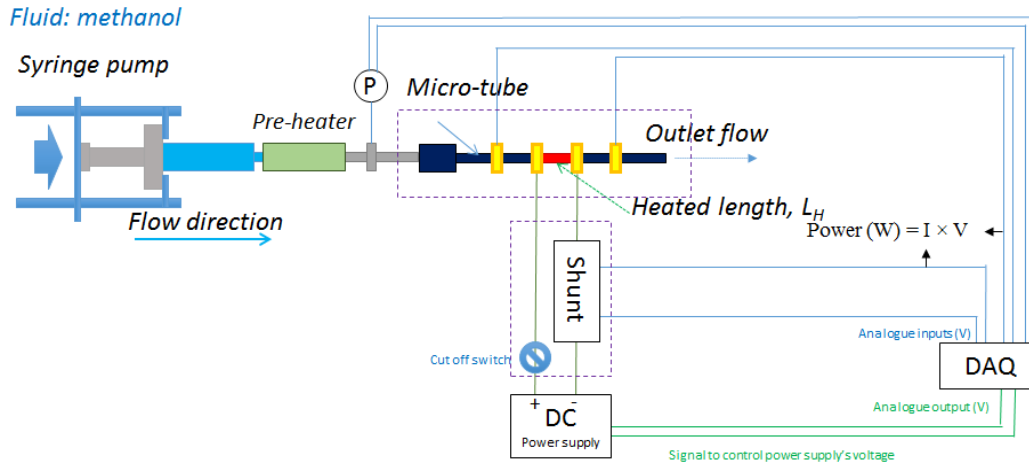


Figure 1 A schematic of the experimental setup

microtubes are very small ($>30\text{ m}\Omega$ depending on the length, and with maximum variation of 8% at highest temperatures) a power supply with high current output (60 amps) was selected. To measure the current through the test section, a $2\text{ m}\Omega$ calibrated shunt was added in series and the voltage across the shunt was measured for current calculation. The delivered power was calculated by measuring the current through and voltage across the heated length. Although, soldering the wires to the microtubes reduced the contact resistances significantly, to eliminate the effect of contact resistance on voltage measurements (for both the shunt and the microtube), a four-probe scheme was used. For this purpose, two additional wires were soldered to the tube to measure the voltage in addition to the two wires delivering current. The uncertainty in power measurement is estimated to be less than 2%.

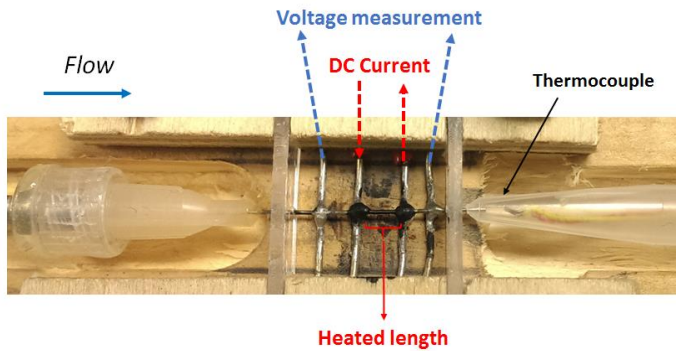


Figure 2 Microtube test section

An omega® pressure transducer (0-690 kPag with maximum uncertainty of $\sim 1.7\text{ kPa}$) monitored the upstream pressure before and during the boiling to identify the single-phase and two-phase pressure drop. To obtain the pressure drop induced by flow boiling, the total single-phase pressure drop (minor and major losses) in the microtube was characterized and subtracted from the total pressure drop measured during the flow boiling. Pressure signal along with the voltage and current was recorded simultaneously in the data acquisition unit for further analysis.

To characterize the CHF, the condition at which the microtube wall was turning in glowing red color (temperatures exceeding $480\text{ }^{\circ}\text{C}$) was chosen as the indication of CHF (which represents poor heat transfer compared to boiling heat transfer). Different flow rates were set by the syringe pump, and delivered power was incrementally ramped up until the CHF condition was observed, and subsequently, the power was cut immediately to avoid any damage to the microtube. In order to calculate the effective wall heat flux, the estimated heat loss was subtracted from the total delivered power, and divided by the heated inner wall area. For the heat loss estimation, the microtube was dried and heated up until it reached the glowing red condition and the corresponding power was recorded. Based on the results, the amount of heat loss was small compared to the heat transferred to the liquid (less than $\sim 5\%$ for smallest flow rate) and it mainly occurred through conduction to the solders.

RESULTS AND DISCUSSION

Single-phase pressure drop

In order to determine the extra pressure drop induced during the two-phase flow (boiling), the pressure drop associated with the single-phase flow was measured. To cross examine the measurements, the single-phase results were compared to the available correlations, however, the measured single-phase pressure drop values were significantly larger than the expected values (mainly due to the contraction region in the entrance of the microtube). To fully resolve the issue, a more careful characterization of the single-phase pressure drop was performed. Total measured single-phase pressure drop is comprised of the minor losses and major losses. To identify the major loss portion of the pressure drop (corresponding to flow in the tube), pressure drop for two lengths of microtube were measured at various flow rates. Based on these measurements, the difference in the pressure drop readings determined the major loss for the difference in tube lengths (cut portion, Fig. 3). Based on this analysis, the corrected values for major loss was obtained and compared with regard to common analytical correlations (Fig. 4). The corrected values for major loss pressure drops are in agreement with the analytical correlations for laminar and turbulent flow. It should be noted that the transition from laminar to turbulent regimes was evident from the slope of the pressure drop data, and occurred in the conventional range of $\text{Re} \sim 2500$.

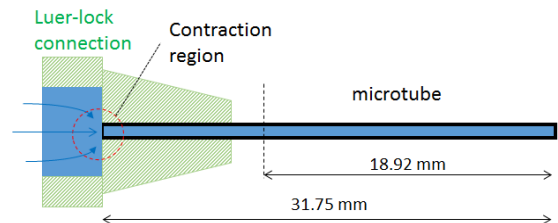


Figure 3 Schematic of microtube connection and cut line for single-phase pressure drop

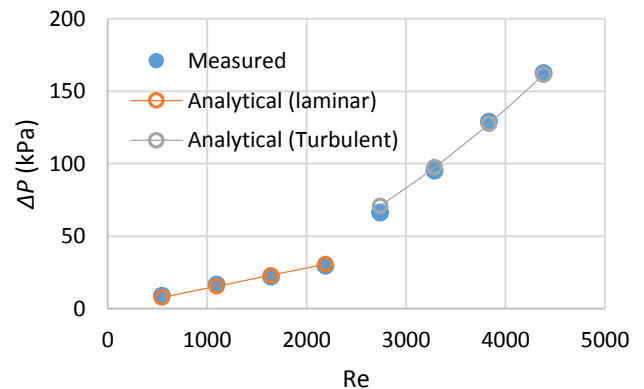


Figure 4 Comparison of major loss pressure drop data with analytical data ID=265 μm

Two-phase pressure drop

The additional pressure drop induced by two-phase flow was considered as the two-phase pressure drop and calculated by subtracting the—total—single-phase pressure drop (power off

mode) from the total pressure drop measured during flow boiling. Figure 5 shows the imposed two-phase pressure drop values for fully subcooled flow boiling ($T_{in} = 23\text{ }^{\circ}\text{C}$) and partially saturated flow boiling cases ($T_{in} \sim 59\text{ }^{\circ}\text{C}$) at $\dot{V} = 15\text{ ml/min}$ ($G \sim 3400\text{ kg/m}^2\text{-s}$). According to the plot, the two-phase pressure drop increases with heat flux, and the pressure drop induced by the saturated boiling case is much higher than the subcooled boiling case. This is attributed to the larger net amount of vapor generated (smaller sensible heat absorbed by the liquid) which contributed to higher velocities and shear forces in the latter case. Furthermore, the lower rate of vapor condensation in saturated boiling case at downstream portion (unheated) of the microtube leads to higher void fraction and consequently higher velocity and pressure drop.

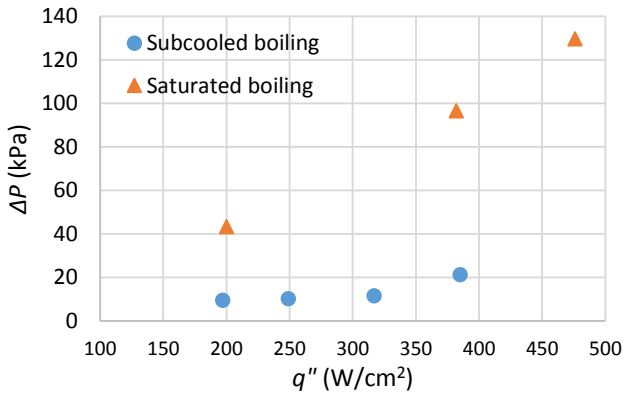


Figure 5 Two-phase pressure drop for subcooled flow boiling and saturated flow boiling; $\dot{V}=15\text{ ml/min}$

Critical heat flux (CHF)

To characterize the CHF, different flow rates were set by the syringe pump, and delivered power was incrementally ramped up until the CHF condition was observed (glowing red color of microtubes) and subsequently the power was cut. Based on the reported correlations in the literature (for both subcooled flow boiling and saturated flow boiling; e.g., [15]), for a fixed fluid properties (h_{fg} , C_p , μ_l , etc.) operating parameters such as inner diameter, mass flow rate, ratio of heated length to inner diameter, and subcooling are particularly important.

To examine the effect of aforementioned parameters, the CHF experiments were conducted for two different heated lengths of 265 μm tube and one heated length of the 150 μm tube, with two inlet temperatures to the test section: liquid at room temperature (subcooled boiling) and elevated inlet temperatures. Figure 6 shows the results of CHF experiments for subcooled flow boiling with room temperature inlet. Based on the collected data, CHF increases almost linearly with Reynolds number (Re) and has higher values at smaller inner diameters. The linear trend is more pronounced for the laminar portion of the plot ($Re < \sim 2500$) as the slope tends to decrease at higher values of Re . This is particularly important for scalability of the results to smaller hydraulic diameters since laminar flow regime is dominant at smaller hydraulic diameters.

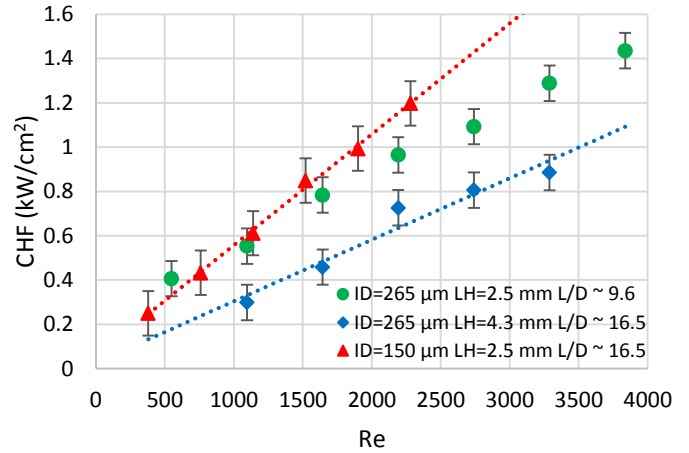


Figure 6 Critical heat flux for a range of operating conditions

To investigate the effect of inner diameter, the ratio of heated length to inner diameter was fixed for two different microtubes with different inner diameters, and the CHF experiments were conducted. For $L_H/D \sim 16.5$, comparing CHF results for $ID = 265\text{ }\mu\text{m}$, $150\text{ }\mu\text{m}$ suggests that CHF is inversely proportional to inner diameter.

To investigate the effect of heated length (L_H/D), CHF was measured for a range of Re at shorter heated length (circular data points, $L_H/D \sim 9.6$ and $ID = 265\text{ }\mu\text{m}$). The CHF for shorter heated length was observed to be higher for the range of the experiments.

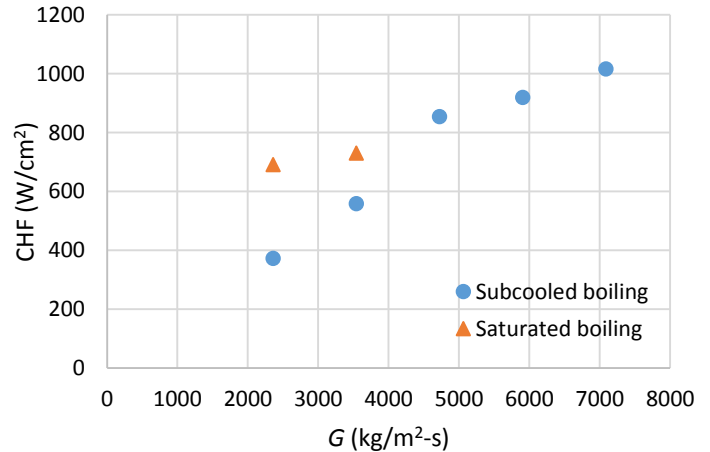


Figure 7 Comparison of CHF for subcooled and saturated flow boiling

To investigate the effect of subcooling on the CHF, for $ID = 265\text{ }\mu\text{m}$ tube and $L_H = 3.7\text{ mm}$ ($L_H/D \sim 14$), methanol was propelled to the test section at two different inlet flow temperatures (room temperature vs. elevated temperature using preheater) and the results were compared (Fig. 7). For elevated inlet temperature case, CHF increased for small flow rates which was in contradiction to the reported trend in the literature. It is believed that the this behavior attributes to the change in boiling

regime, however, further investigation, especially with flow visualization is required to explain the phenomenon. It should be noted that due to the very large two-phase pressure drop compared to subcooled boiling case (refer to Fig. 5)—reaching the maximum pumping capability of the syringe pump—the experiments were limited to mass flow rates smaller than 3400 kg/m²-s.

CONCLUSION

Pressure drop and CHF for flow boiling of methanol with very high heat fluxes (exceeding 1 kW/cm²) was studied using stainless steel microtubes. Two-phase pressure drop increases with increasing the flow rate for both subcooled boiling and saturated boiling cases, however, based on the collected data, the pressure drop induced by the subcooled boiling was significantly smaller than the saturated flow boiling. This is particularly important as it decreases the operational cost and capital cost associated with the two-phase flow delivery loop. The results of the CHF experiments suggests that the subcooled boiling CHF increases almost linearly with Re (especially at laminar regime) and inverse of inner diameter, and decreases with increasing L_H/D .

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NOMENCLATURE

C_p	specific heat
D_h	hydraulic diameter
G	mass velocity
h_{fg}	latent heat of evaporation
$ID (D)$	inner diameter
k	thermal conductivity
P	pressure
q''	heat flux
Re	Reynolds number
T	Temperature

Greek Symbols

Γ	volume flow rate
k	thermal conductivity
ρ	density
μ	dynamic viscosity

Subscripts

H	heated
in	inlet
l	liquid

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