Effect of ionic liquid additives on temperature and pressure fluctuations during water flow boiling in microchannels

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Abstract. Overheating of high-performance electronic devices is undesired for long-term reliability. In this regard, two-phase microchannel heat sinks promise high heat dissipation within small temperature budgets using the latent heat of vaporization of the boiling fluid. However, geometrical confinement induces thermofluidic fluctuations and prohibits the use of two-phase microchannel heat sinks in practical applications. Here we for the first time report flow boiling experiments with surface-active ionic liquid (SAIL) as an additive in water. This concept is inspired by our results of pool boiling wherein bubble coalescence was avoided with SAIL. In comparison to the water where fluctuations were apparent in the slug flow regime, temperature and pressure fluctuations were nearly mitigated up to the heat flux of 700 kW/m² with an ionic liquid solution. The suppression of instabilities is attributed to the delay in the formation of a big vapor bubble at the inlet of microchannels due to the non-coalescing nature of bubbles formed with the SAIL solution.

1. Introduction

The miniaturization of electronic devices has increased thermal management challenges. In this regard, two-phase microchannel heat sinks promise high heat dissipation due to the latent heat of vaporization of the fluid. However, the instabilities induced due to geometrical confinement prohibit the use of two-phase microchannel heat sinks in real-life applications. The vapor bubbles coalesce quickly and grow in the transverse direction restricting the flow of water due to the small size of the channels. When the inertia of incoming subcooled liquid becomes large enough to rupture the vapor bubble, flow is established again [1].

Wu et al. [2] used silicon microchannel as a test section in flow boiling experiments with water, and temperature and pressure fluctuations were observed due to instabilities. Jeong et al. [3] conducted experiments with tri-sodium phosphate as an additive with water in a circular stainless steel tube and reported around 48% enhancement in CHF in comparison to pure water at low mass fluxes (100-300 kg/m²s). Wang et al. [4] used rectangular channels of polycarbonate with nickel foil as the heating surface and Cetyltrimethyl ammonium chloride (CTAC) with Sodium salicylate (NaSal) as the additives. An increase in the heat transfer coefficient (HTC) with an increase in the concentration was observed up to the concentration of 100 ppm, beyond which the HTC started decreasing. Similarly, Wang [5] reported stronger pressure fluctuations with a surfactant solution in comparison to water. All these studies typically use surfactant as an additive, but the use of ionic liquid which has shown
significant heat transfer enhancements during pool boiling has yet not been explored. When the ionic liquid is used as an additive in pool boiling, both CHF and HTC are enhanced in comparison to the surfactant solution [6]. Here we report results of flow boiling experiments with surface-active ionic liquid-based aqueous solutions used as the test fluid. We discuss the impact on temperature and pressure fluctuations.

2. Experimental setup
Experiments were performed on a custom-built, hermetically sealed closed flow loop as shown in Figure 1. The fluid was first of all degassed in a degassing chamber. The degassed fluid was pumped using a peristaltic pump which was also used to control the mass flux. An accumulator was connected just after the pump to mitigate pulsations from the peristaltic pump. A preheater was connected after the accumulator to maintain inlet fluid subcooling equal to about 20 K. The fluid passed through microchannels within the test section where boiling took place. Power was supplied to the preheater using a variable auto-transformer. Thermocouples and pressure sensors were connected to their respective positions and proper arrangements were made to make every connection leak-proof. The fluid next entered the condenser where it rejected heat and entered back into the degassing chamber, thereby completing the loop. Temperature and pressure data were obtained by using a data acquisition unit at a frequency of 1 Hz. Images with a resolution of 800x600 pixel were captured at 1000 frames per second and 5000 frames per second using a high-speed camera (Vision Research, Phantom v7.3).

![Figure 1. Schematic of the flow loop. 1 – degassing chamber; 2 – valve, 3 – pressure gauge; 4 – pump; 5 – accumulator; 6 – preheater; 7 – variable auto-transformer; 8 – test section; 9 – differential pressure transducer; 10 – absolute pressure transducer; 11 – condenser; 12 – Data Acquisition Unit.](image-url)

The test section was a stepped copper block as shown in Figure 2 with the bottom section as a 30 mm×30 mm×40 mm cuboidal block and the upper neck portion having the dimensions of 10 mm×10 mm×20 mm. Sixteen microchannels were fabricated on the topmost portion of the copper block using CNC Wire Electrical Discharge Machining (Wire-EDM). Each microchannel was 500 µm deep and 300 µm in width. A cartridge heater (Omega, HDC00004) with a power rating of 500W was inserted into the copper block from the bottom in order to mimic the thermal load on a typical electronic chip. Three thermocouples T3b, T5h, and T7h were inserted 4 mm below the bottom surface of the central microchannel to measure the temperature variation in the longitudinal direction. Two thermocouples (T7v and T10v) were placed in the transverse direction right below T3b to facilitate heat flux calculations.
The copper block was covered with Teflon insulation to prevent heat losses. The horizontal-inlet manifold and horizontal-outlet manifolds (HH) were integrated into the Teflon block. Two ports were also fabricated in the Teflon block for the connection of pressure transducers. An absolute pressure transducer (Omega, PX951-050G5V) was connected at the outlet plenum and a differential pressure transducer (Omega, PX81D6-005DV) was connected across the microchannels to measure the pressure drop during experiments.

![Figure 2](image)

Figure 2. (a) Sectional view of the test section; (b) CAD model of test section (all dimensions are in mm).

In this study, the surface-active ionic liquid solution was used as the test fluid. Ionic liquids are molten salts at room temperature with very low vapor pressure, are non-volatile, and stable at higher temperatures [7]. Ionic liquids containing longer alkyl chain are amphiphilic and often referred to as surface-active ionic liquids (SAILs). When bubbles are formed during boiling, these molecules adsorb at the liquid-vapor interface such that the hydrophobic tail resides in the vapor while the hydrophilic part remains in liquid. These ionic liquid laden interfaces repel from each other when bubbles come close. Thus, unlike pure water where instantaneous coalescence is observed, the ionic liquid solution avoids bubble coalescence. As a result, SAIL has been shown to demonstrate significant enhancement in pool boiling heat transfer [6]. Here we report the first experiments on flow boiling with surface-active ionic liquid as an additive in water. The additive used in the experiment is an aqueous solution of 1-Butyl-3-methylimidazolium octyl sulphate ([C₄mim][OS]) at 625 ppm. The critical micelle concentration of this additive is 10,000 ppm.

3. Results

We now compare the bubble behavior with both fluids. For the experiments with water, nucleation is followed by the slug flow regime. These slugs eventually coalesce together causing complete dryout of microchannels. In the individual microchannels backflow result in the formation of big vapor bubbles at the inlet and outlet of microchannels as shown in Figure 3. The pressure buildup due to the incoming liquid at the inlet eventually dominates and ruptures the big bubble leading to flooding of microchannels. In comparison, the formation of a big bubble is avoided in the case of ionic liquids. As a result, it is easy to rupture the multiple bubbles at the inlet as shown in Figure 4. Accordingly, extended dryout, as observed in the case of water, is delayed in case of ionic liquids.
Figure 3. Cyclic flow pattern when water is used as a test fluid.

Figure 4. Cyclic flow pattern when the ionic liquid solution is used as a test fluid.
3.1. Temperature fluctuations

Next, compare data of temperature and pressure fluctuations with water and SAIL solution. These estimations are based on the standard deviation from the time-averaged mean value (±σ). The standard deviation is calculated using the formula given below:

\[ \sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N}} \]  

(1)

where \( \mu \) is mean of obtained data, \( x_i \) is data obtained at each point, and \( N \) is the number of data. For +σ the data having a value of \( x_i \) greater than \( \mu \) is considered. Similarly, for −σ, the value of \( x_i \) lower than \( \mu \) is considered and the same step is repeated.

The comparison of temperature fluctuation with water and aqueous ionic liquid solution for an effective heat flux of 700 kW/m² is shown in Figure 5. From this Figure, it is apparent that the fluctuations are almost absent in the case of the ionic liquid solution because the duration of dryout of microchannels in the case of water is higher than that of ionic liquid solution. For the ionic liquid solution, rewetting was followed by the complete flooding of microchannels. For water, rewetting causes slug flow which decreases heat transfer resulting in higher average temperature. In the case of an ionic liquid solution, thin-film evaporation was observed which was not so evident at these heat fluxes in the case of water.

![Figure 5](image)

**Figure 5.** Temperature fluctuations at 700 kW/m² with (a) water and (b) ionic liquid solution as the test fluid.

The temperature fluctuation is next compared at an effective heat flux 900 kW/m² in Figure 6. When temperature fluctuations for the ionic liquid solution at the heat fluxes of 700 and 900 kW/m² are compared, much larger fluctuations were observed at the heat flux of 900 kW/m². This is mainly due to the prolonged dryout at a heat flux of 900 kW/m². At the heat flux of 700 kW/m² the dryout duration was very short so that the thermal penetration depth in the substrate (proportional to the square root of the duration) was less than the thermocouple insertion depth (4 mm). At 900 kW/m² thin-film evaporation regime was also evident making the average temperature lower in comparison to water, but this effect is not as evident as it was for previous heat flux.

3.2. Pressure fluctuations

Figure 7 shows pressure fluctuation across the microchannel for effective heat of 700 kW/m². It can be seen that the average pressure difference across microchannel in the case of both water and ionic liquid solution are almost similar, but the fluctuation from average data is lower in the case of ionic liquid solution. Vapor bubble formed at inlet plenum rupture early in ionic liquid solution in comparison to water due to reduced surface tension. In the case of ionic liquid solution, bubble coalescence is
avoided resulting in the formation of small bubbles at the inlet. These bubbles rupture quickly leading to high-frequency rewetting and thus stabilizing temperature and pressure fluctuations.

**Figure 6.** Temperature fluctuation at 900 kW/m$^2$ with (a) water and (b) ionic liquid solution as the test fluid.

Similarly, at a heat flux of 900 kW/m$^2$, the pressure fluctuation is lower in the case of ionic liquid in comparison to water since it is easier to rupture vapor bubbles formed in ionic liquid solution due to reduced surface tension. Hence, the pressure buildup at the inlet is not high and thus the fluctuation is less, as shown in Figure 8.

**Figure 7.** Pressure fluctuation across microchannels at 700 kW/m$^2$ with (a) water and (b) ionic liquid solution.
**Figure 8.** Pressure fluctuation across microchannel at 900 kW/m$^2$ with (a) water and (b) ionic liquid solution as test fluid.

**Conclusions**

We performed flow boiling experiments in a microchannel with the aqueous ionic liquid solution, to study its effects on temperature and pressure fluctuation. With the aqueous ionic liquid solution, temperature and pressure fluctuations were almost mitigated up to a heat flux of 700 kW/m$^2$. The property of ionic liquid to avoid bubble coalescence helps in the formation of small vapor bubbles at the inlet and outlet of microchannels. These small vapor bubbles at the inlet are easily ruptured and thus facilitate complete flooding of microchannels minimizing the period of dryout. Once heat flux is further increased beyond 700 kW/m$^2$, the bubbles formed at the inlet are forced to coalesce due to the quick evaporation of the liquid layer trapped between the bubbles. Thermohydraulic performance similar to water is obtained. These results suggest that aqueous ionic liquid solution can be used for instability mitigation and cooling of electronic devices up to moderate heat fluxes.

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