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ENHANCEMENT OF POOL BOILING AND CRITICAL HEAT FLUX IN SELF-REWETTING FLUIDS AT ABOVE ATMOSPHERIC PRESSURES

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ABSTRACT

Pool boiling experiments have been conducted with a self-rewetting fluid consisting of an aqueous butanol solution to study the boiling heat transfer enhancement at pressures of 1 ~ 4 bars. Although self-rewetting fluids have been used to enhance the performance of heat pipes, boiling heat transfer characteristics are yet to be fully understood especially at pressures above atmospheric. Pool boiling experiments with aqueous butanol solutions were performed using an electrically heated platinum wire to obtain pool boiling heat transfer data up to the Critical Heat Flux (CHF). Aqueous butanol solutions with butanol concentrations 2-7% showed enhanced heat transfer coefficients and CHF data at various pressure levels. In comparison to water, aqueous butanol solutions showed 20-270% higher values of CHF at pressures up to 4 bars. The bubble sizes were also observed to be significantly smaller in self-rewetting fluids compared to those in water at the same pressure. This observation was consistent even at higher pressures. However, for the highest butanol concentration tested (7%), the CHF enhancement was diminished at higher pressures.

INTRODUCTION

Boiling heat transfer has been and will remain a very efficient way of transporting heat in direct or indirect heat exchange processes. This is due to higher heat transfer rates per unit area due to bubble nucleation and micro-convection currents. Due to substantially high heat transfer rates, it is a good contender for electronics cooling applications as well. In pool boiling, heat flux increases with wall superheat until it

reaches a critical heat flux (CHF) after which the heat transfer coefficient starts deteriorating rapidly and dry-out of the heat transfer surface occurs.

The most effective approach to increase CHF has been to engineer the properties of surface or fluid, without changing operating variables. Some of these approaches for increasing CHF are using fluid mixtures (van Starlen, 1969) instead of pure liquids, changing the composition of fluid mixtures, and adding surfactants or nanoparticles. In the last decade, nanofluids have been in spotlight for attaining higher CHF values, but the reason was attributed to nanoparticle deposits which increase the surface wettability.

Recently, it was reported by Nishiguchi et al. (2008) that low concentrations (2% - 7%) of butanol in water resulted in 20-50% increases in CHF values at atmospheric pressure conditions. In order to achieve higher CHF values, classical approaches have been to vary system thermodynamic conditions such as increases in pressure and sub-cooling. Nishiguchi et al. (2009) showed that CHF increases with increased sub-cooling for low butanol concentrations. It was also shown in their work that under the same conditions for saturated or subcooled butanol mixtures, two different modes of boiling could be observed: ordinary boiling (OB) and small bubble emission boiling (SEB). The SEB is different from ordinary boiling because the number of bubbles is larger and average bubble size is smaller, which makes it an interesting choice for small scale applications. Under such SEB mode, CHF could be 2-3 times that of water. An explanation for such different modes of boiling does not yet exist which makes it difficult to engineer the enhancement effect.

In the presence of sub-cooling, Nishiguchi et al. (2009) showed that the CHF value for a 3% butanol mixture at atmospheric pressure is comparable to CHF values for water at 7 bars. Importance of strong non-linear dependence of surface tension on temperature was highlighted for butanol mixtures and it was speculated to have an impact on the observed behavior in pool boiling experiments. However, these experiments were carried out at atmospheric pressure conditions only. Therefore, the observations were limited up to the saturation temperature corresponding to atmospheric pressure. In this work, the pool boiling behavior of butanol-water mixtures at higher pressures is investigated.

In most pure liquids, increases in pressure have shown increases in CHF at least up to reduced pressure values of 0.35 above which the CHF starts decreasing. An initial increase in pressure from atmospheric condition leads to smaller bubble sizes, therefore bubble coalescence is inhibited or reduced at the same heat flux. It is known from the literature (Vochten, 1973) that surface tension increases with temperature for aqueous butanol solutions contrary to pure water where surface tension continuously decreases with temperature. But only a limited amount of surface tension data, up to 100 °C, is available for such mixtures. Therefore saturated boiling experiments at pressures and temperatures above 1 atmosphere and 100 °C have been performed in this work to determine the impact of increasing surface tension on pool boiling and CHF of self-wetting fluids.

APPARATUS AND METHODS

The experimental setup used in the present pool boiling experiments (Fig.1) is similar to the apparatus used in atmospheric pressure pool boiling experiments by Nishiguchi et al. (2009). A stainless-steel vessel, with glass windows for visual observation, was filled with water or an aqueous butanol solution. The vessel was able to withstand and maintain high pressures well above 10 bars. Higher pressures above atmospheric were achieved by using compressed air from an oil-free air compressor. A pressure gauge was mounted on the vessel which had an accuracy of +/- 0.035 bar. An auxiliary voltage-controlled heater tape (Omega HTWC101-006) was wrapped around the vessel to heat the liquid inside and maintain its temperature constant at a saturation temperature corresponding to the specified system pressure. The accuracy of the thermocouple used for liquid temperature measurement was +/- 0.2°C. Controlling the input power supplied to the heater tape allowed maintaining a precise and steady bulk liquid temperature. Moreover, the heater tape was used to heat the vessel uniformly from all sides in order to avoid a strong buoyancy effect and maintain a uniform temperature in the fluid.

The heater surface under observation was a horizontal platinum fine wire suspended between two copper electrodes immersed in the liquid. Two ends of the platinum wire were soldered to the copper electrodes which were connected to a DC power supply (Sorensen XTR6-110). Platinum is preferred

for its resistance to corrosion and highly repeatable resistance-temperature characteristics. A low voltage, high current from the DC power supply was able to generate uniform heat flux across the surface of the platinum wire and steady in time. The diameter and length of the platinum wire were fixed to be 250 μm and 21mm, respectively. A thermocouple was located 10 mm below the platinum wire to monitor the bulk liquid temperature.

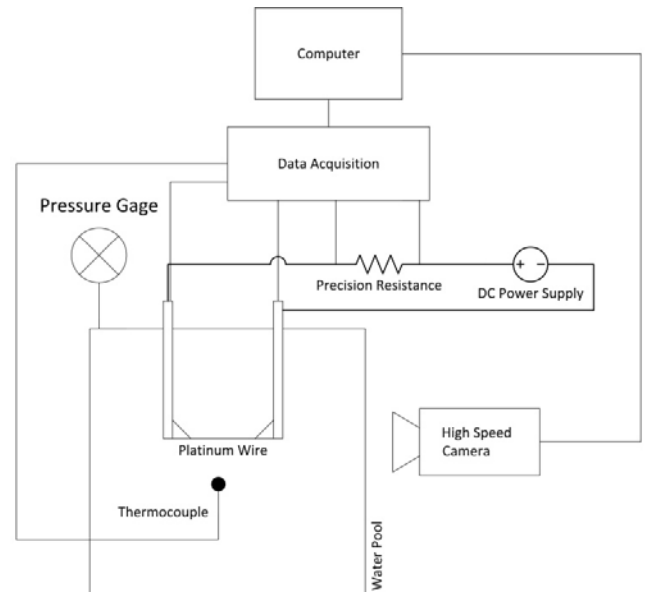


FIGURE 1: EXPERIMENTAL ARRANGEMENT FOR THE POOL-BOILING SET-UP

Since the DC current passing through the platinum wire was high, it was measured indirectly with a precision resistor (Vishay LVR5 .005) of low electrical resistance ($R_s=0.005$ Ohm) connected in series with the platinum wire. The voltage drop (E_s) across the precision resistor and the resistance R_s was used to obtain the current ($I=E_s/R_s$) flowing through the platinum wire as well as the precision resistor. A voltage drop (E) across the platinum wire itself was also measured, and using the calculated DC current (I), the resistance of the platinum wire (R) was determined using Ohm's law ($R=E/I$). Moreover, the heat flux was determined from the electric power consumed ($P=EI$) and the surface area of the platinum wire, A_s . To determine the wire temperature, its electrical resistance was recorded at different temperatures under adiabatic conditions. A linear relationship existed between the platinum resistance and temperature $R = R_0 [1 + \alpha (T - T_0)]$. This linear relationship was used to obtain the wire temperature from the measured resistance. The uncertainties in the system pressure, heater power, heat flux, heater wire temperature and fluid temperature were calculated using the propagation of error analysis and are summarized in Table 1.

In the experiments, the heat flux from the platinum wire was raised by controlling the applied voltage, until the CHF

condition was reached as indicated by a sudden increase in the wire temperature as the heat flux was incrementally increased.

TABLE 1: UNCERTAINTY ESTIMATES

Quantity	Estimated Uncertainty	Range
Pressure	0.035 bar	1 - 4 bars
Heater Power	1 mW	10-40 W
Heat Flux	67 W/m ²	0 - 3x10 ⁶ W/m ²
Heater Wire Temperature	1°C	90-120°C
Fluid Temperature	0.2 °C	90 - 150 °C

In this work, tests were first performed with distilled water at different pressures, over an increment of 1 atm, and three sets of CHF data for each pressure setting were obtained and compared to literature values. These CHF values matched well with the existing literature data for water within an order of 10%. After these experiments, butanol and distilled water were mixed to obtain butanol concentrations of 2%, 5% and 7% by weight. For each aqueous butanol solution, pressure was raised incrementally to check CHF for each solution. All the tests were performed at near saturation temperature. The effect of dissolved air in the solution was minimized by boiling the distilled water prior to use in the experiment. Moreover, the pressure vessel was filled completely with the solution in order to reduce the presence of air. Maintaining a constant pressure throughout the experiment was achieved by circulating a heating/cooling fluid through a copper coil placed inside the pressure vessel. A constant temperature circulator (VWR 1166D) was used to maintain the heating/cooling fluid at the desired saturation temperature in order to avoid pressure build-up in the pressure vessel. To study the bubble nucleation, growth and departure from the platinum wire, a high speed video camera (Phantom V310) and a digital camera were used.

Experiments were conducted at saturation temperatures corresponding to four different pressures, P=1.0, 2.0, 3.0 and 4.0 bars, using aqueous butanol solutions with three different butanol concentrations, 2%, 5% and 7% by weight. The saturation condition was observed physically from the behavior of vapor bubbles not condensing in the bulk liquid after departure from the platinum wire. This is due to the unavailability of saturation temperature data for aqueous butanol solutions at higher pressures. The test conditions covered in the present work are tabulated in Table 2 and experiments were repeated several times for each pressure. The corresponding saturation temperatures are listed in Table 2 for respective tests. Aqueous butanol solutions are non-ideal solutions and have a lower boiling point than pure water. Higher butanol concentrations also resulted in lower boiling points.

TABLE 2: TEST CONDITIONS AND CORRESPONDING SATURATION TEMPERATURES

	1 Bar	2 Bars	3 Bars	4 Bars
Water	99.8°C	121°C	134.5°C	145°C
2% Butanol	98°C	119.1°C	132.1°C	142°C
5% Butanol	95°C	115.5°C	128°C	136.5°C
7% Butanol	93°C	113°C	127°C	135°C

RESULTS

Small Bubble Emissions

Similar to the previous work by Van Starlen (1963) and Nishiguchi et al. (2009), aqueous butanol solutions showed the small bubble emission (SBE) behavior even at very low concentrations of butanol. This was consistently observed between the lowest and highest concentrations of the butanol solution tested under saturated boiling conditions. The reason for this very small bubble emission behavior in the aqueous butanol solution is yet unclear. Some of the bubbles were observed to move downward after breaking off from the heated wire before rising upwards. This may be due to an initial bubble momentum being greater than the buoyancy force.

The heat flux versus wall superheat data (Fig. 2) shows a negative slope in some regions which is similar to the observations reported by Nishiguchi et al. (2009). Pressure does not have a significant impact on the bubble size in the case of butanol solutions in contrast to pure water where the effect is easily discernible in the range of 1-4 bars. Previous authors (Fumoto et al., 2010; Nishiguchi et al., 2009; Savino et al., 2010) mentioned that at low concentrations, thermophysical properties such as density, specific heat, thermal conductivity and latent heat do not change significantly. Ono et al. (2007a) showed the surface tension data for aqueous butanol solutions up to 100 °C. Surface tension of butanol solutions increased with temperature, so increasing the pressure and temperature should increase the surface tension value. The surface tension of saturated water at 4 bars, i.e. 50 dynes/cm, is less than the surface tension of an aqueous butanol solution under saturation conditions at atmospheric pressure. Therefore, smaller bubble sizes in the case of an aqueous butanol solution in pool boiling cannot be explained by the surface tension effect alone. As stated earlier, aqueous butanol being positive deviation non-ideal solution, it has a higher total vapor pressure at any corresponding temperature which might be the cause of smaller bubbles. It is hard to prove this hypothesis with the current experimental set-up which is mainly designed for CHF experiments.

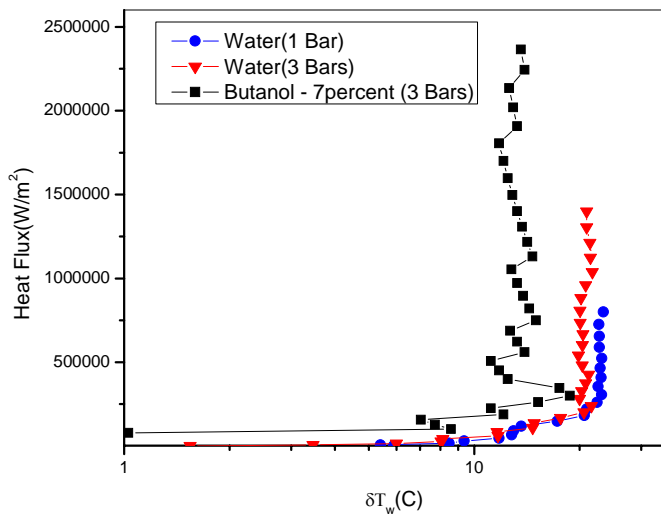


FIGURE 2: HEAT FLUX VS. WALL SUPERHEAT FOR WATER AND AQUEOUS BUTANOL SOLUTION AT SATURATION TEMPERATURE

Effect of Butanol Concentration

The present data for the aqueous butanol solutions exhibited substantial increases in CHF even at higher pressures. Even for the lowest butanol concentration of 2%, small bubble emissions were consistently observed at all pressures as shown in Fig. 3. This small bubble emission boiling might be the reason for higher CHF values at all pressures tested. With the present experimental data, however, it was difficult to quantify the reduction in bubble size with increases in pressure for aqueous butanol solutions. It is also observed that the wall superheat is lower as compared to that for pure water for corresponding CHF. Increasing the butanol concentration decreases the saturation temperature therefore

decreases the surface tension ($\frac{d\sigma}{dT} > 0$, Ono et al., 2007).

However, sufficient data at higher temperatures is not available to validate this hypothesis.

Effect of Pressure

Before proceeding to the aqueous butanol solutions, the system was first tested to obtain CHF with pure water at higher pressures. The test results were found to be consistent with the literature values of CHF for water. In Figs. 4-6, the water data are compared with Zuber's correlation (1959) for an infinite size heater surface multiplied by 0.75 to account for the reduced heater size in the present work. The increase in CHF with pressure for aqueous butanol solutions was nearly the same at all butanol concentrations tested. As the pressure was increased, the CHF for both water and aqueous butanol solutions almost doubled in value reaching ~1.5 and ~2.4 MW/m² at 4 bars.

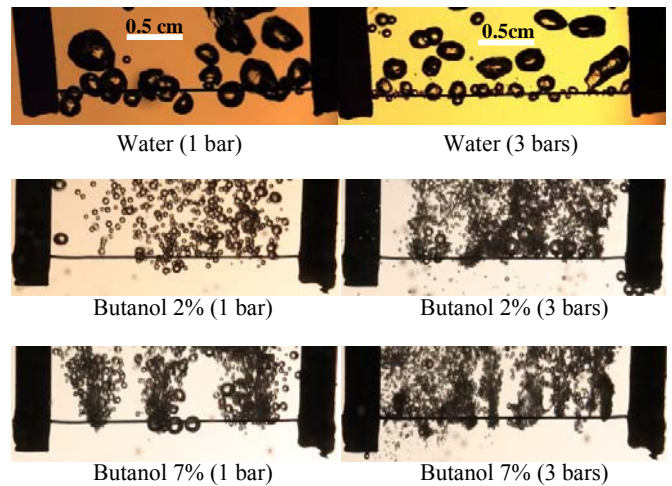


FIGURE 3: BUBBLE DIAMETER CHANGES AS A RESULT OF BUTANOL CONCENTRATION AND PRESSURE

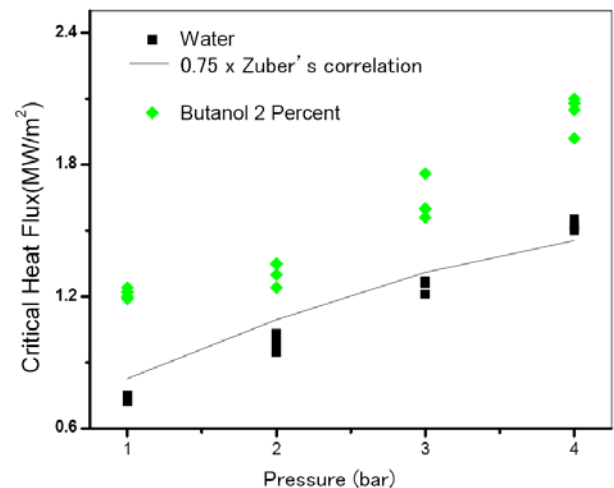


FIGURE 4: COMPARISON OF CHF VALUES FOR WATER AND AQUEOUS BUTANOL SOLUTION (2%) AT DIFFERENT PRESSURES

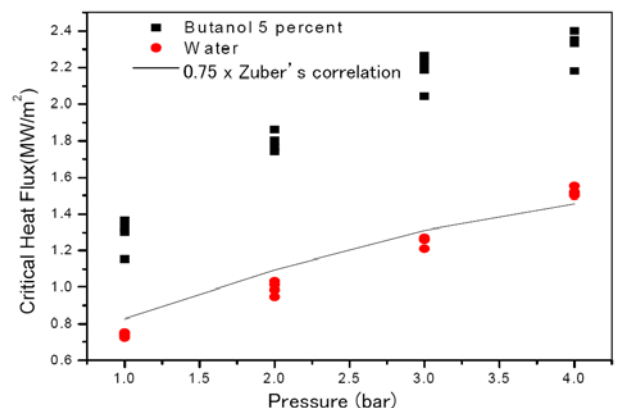


FIGURE 5: COMPARISON OF CHF VALUES FOR WATER AND AQUEOUS BUTANOL SOLUTION (5%) AT DIFFERENT PRESSURES

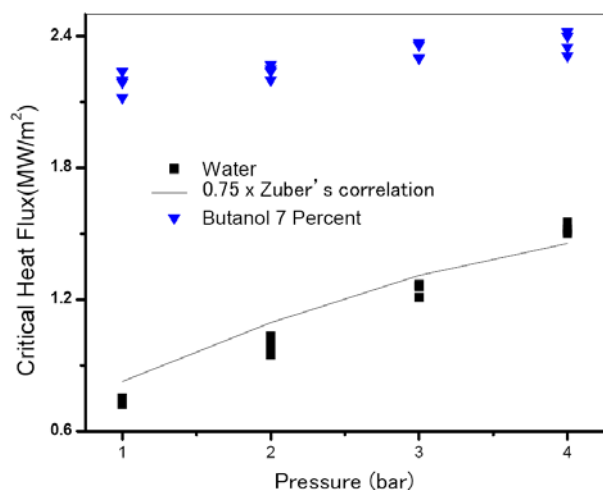


FIGURE 6: COMPARISON OF CHF VALUES FOR WATER AND AQUEOUS BUTANOL SOLUTION (7%) AT DIFFERENT PRESSURES

Figure 7 shows the CHF ratio relative to water for 2, 5 and 7% butanol solutions at different pressures. At lower pressures (up to 2 bars), the CHF ratio increased in value with increased butanol concentrations (5% and 7%), however, at higher pressures (3 and 4 bars), the CHF ratio was the same between 5% and 7% butanol concentrations as shown in Fig. 7. For the 7% butanol solution, the increase in CHF with pressure was the smallest (Fig. 6), so the CHF ratio decreased with an increasing pressure (Fig. 7).

Although the CHF ratio is somewhat reduced at higher pressures, the CHF enhancement is clearly achieved at higher pressures by using an aqueous butanol solution. Thus, there appears to be an advantage in increasing the butanol concentration to above 5% at higher pressures from a CHF perspective. Currently there exists no explanation for this enhancement effect and this will be the topic for future research after gaining some knowledge of vapor pressure and surface tension variations for such non-ideal mixtures.

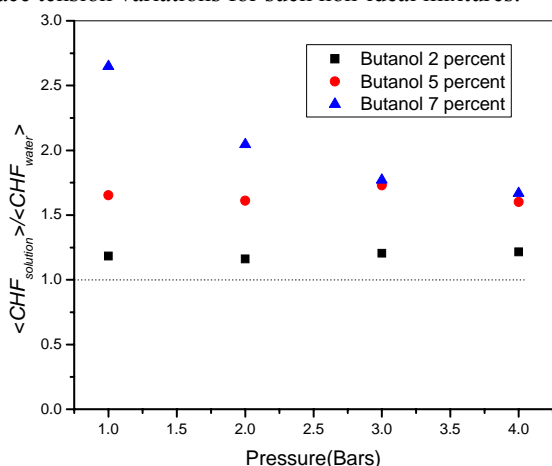


Figure 7: OVERALL EFFECT OF PRESSURE AND BUTANOL CONCENTRATION ON CHF RATIO

CONCLUSIONS

Saturated pool boiling experiments at pressures between 1 and 4 bars showed that small bubble emission is a consistent boiling phenomenon for aqueous butanol solutions with butanol concentrations up to 7%. Reasons for such small bubble sizes cannot be due to the surface tension of the fluid alone which is speculated to be higher than or at least equal to water at higher pressures. Increases in butanol concentration consistently led to increased CHF values even at higher pressures. For 2 and 5 % butanol concentrations, the increase in pressure caused large increases in CHF similar to that obtained with water. However, the system pressure did not have a significant effect on CHF for the highest butanol concentration (7%) tested. Small bubble emission (SBE) boiling and higher CHF values may be attributed to higher total pressure of non-ideal mixtures, but more research needs to be conducted to verify this hypothesis.

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