

An experimental study of boiling in dilute emulsions, part A: Heat transfer

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Abstract

Results are reported of an experimental study of heat transfer in pool boiling of dilute emulsions of pentane in water and FC-72 in water. Heat transfer coefficients for single phase convection, boiling of the dispersed component, and enhanced boiling of the continuous component are reported. Results show that the boiling heat transfer coefficient is a function primarily of superheat of both the dispersed component and continuous component, sub-cooling of the bulk of the emulsion, and volume fraction of the dispersed component up to ~ 1 %. Other properties of the dispersed component are relatively unimportant, as are the geometry of the heated surface and droplet size of the emulsion. Droplets of the dispersed component can accumulate on the heated surface, but this accumulation affects heat transfer only in single phase convection.

Key words: emulsion, heat transfer, boiling

Nomenclature

C_{sf}	Empirical surface-fluid factor in Eq. (2)
c_p	Constant-pressure specific heat, kJ/kg-°C
d	Diameter, m
g	Acceleration due to gravity, 9.81 m/s ²
h	Heat transfer coefficient, W/m ² -°C
i	Specific enthalpy, J/kg
k	Thermal conductivity, W/m-°C

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Nu	Nusselt number, hd_{wire}/k
Pr	Prandtl number, ν/α
q''	Heat flux, W/m^2
Ra	Rayleigh number, $\frac{g\beta_{\text{film}}(T_s - T_\infty)d^3}{\nu_{\text{film}}^2} Pr_{\text{film}}$
s	Prandtl number factor in Eq. (2)
T	Temperature, K
ΔT	Temperature difference, $T_{\text{wire}} - T_\infty$

Greek Symbols

α	Thermal diffusivity, m^2/s
β	Volumetric expansion coefficient, m^3/m^3-K
ϵ	Dispersed component volume fraction, % m^3/m^3
μ	Dynamic viscosity, $kg/m-s$
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Surface tension, N/m

Subscripts

lph	Single phase convection
b	Bubble
c	Continuous phase
d	Droplet
f	Saturated liquid
fg	Difference between saturated vapor and saturated liquid
film	Evaluated at film temperature, $(T_{\text{wire}} + T_\infty)/2$
g	Saturated vapor
sat	Saturated condition
wire	Heated wire
∞	Bulk condition

1. Introduction

Boiling has long been recognized as an important heat transfer mechanism and has been studied intensively for over a century. The mechanisms of boiling of pure liquids are now fairly well understood, but surprising behavior is still encountered in some circumstances. One area that is not yet understood is boiling of dilute emulsions in which the dispersed component has a lower boiling point than the continuous component. Boiling heat transfer in emulsions was first studied in the 1970's [1], and dilute emulsions have since been studied extensively by Bulanov and co-workers [2-4]. This area of study is distinct from combustion of emulsions of water and liquid fuels, which is characterized by evaporation at the free surface of the emulsion droplet and combustion of the fuel. In contrast, in studies of boiling emulsion heat transfer, the bulk of the emulsion remains liquid, and no chemical reactions occur. A review of prior work in this field may be found in [5]. Despite these experimental studies, there is as yet no detailed understanding of how the boiling process occurs, and the range of experimental data in the literature is quite limited.

An emulsion is a mixture of two immiscible liquids in which one liquid (the dispersed component) forms a suspension of many small droplets in the other liquid (the continuous component). For heat transfer applications, an emulsion is considered dilute when the dispersed component occupies ~5 % or less of the emulsion by volume. For the emulsions used in this study the dispersed component has a significantly lower boiling point than the continuous component. In this study heat transfer to emulsions is measured for single phase heat transfer, boiling of the dispersed component only, and boiling of both the dispersed and continuous components.

The purpose of this study is to extend the experimental data base to combinations of liquids that may be of practical use in cooling high power electronic devices. Most published experimental studies use emulsions of water and oil at atmospheric pressure, so that heat transfer enhancement due to boiling of the emulsion occurs at temperatures greater than 100 °C [1-4]. In contrast, current solid state electronic devices must generally operate at temperatures below 85 °C [6]. The dispersed component must, therefore, have a much lower saturation temperature than water. Water is suitable for use as the continuous component, where its high thermal conductivity and specific heat are advantageous for heat

transfer applications. Experiments are performed with two different fluids, FC-72 and pentane, each emulsified in water. FC-72 is a FluorinertTM electronic liquid manufactured by 3MTM. Currently, the open literature does not contain any data on boiling emulsions of these fluid combinations. This paper discusses heat transfer measurements, and part B [7] reports visual observations of the boiling emulsions.

We examine emulsions undergoing free convection boiling on a horizontal heated wire. Although practical applications such as electronics cooling would likely involve flow boiling in small-diameter channels, the free convection apparatus used in this study offers a better opportunity to observe the detailed behavior of boiling emulsions and also allows comparison between the results of this study and those of previous studies.

2. Apparatus and procedure

The test chamber (Fig. 1) is constructed of clear acrylic and has a volume of 1 L. The width of the chamber is small (25 mm) so that visual observations may be made for very dilute emulsions. The heat transfer surface is a fine wire of pure copper that has a diameter of 101 μm diameter and a length of 100 mm. The wire is stretched between two bus bars in a horizontal orientation and is heated electrically using a current-controlled DC power supply. The duration of each experiment is short enough that additional equipment is not required to maintain a nearly constant bulk temperature in the emulsion during each experiment. The wire is replaced before each experiment to ensure that neither corrosion nor accumulation of foreign material changes its surface properties.

The voltage difference across and electrical current through the wire are measured and are used to calculate surface heat flux and temperature from the electrical resistance. Because the ratio of wire length to diameter is large (~ 1000), the wire has constant temperature along most of its length. Only a minor correction is necessary to account for the temperature variation at its ends. The wire is essentially isothermal throughout its cross-section as well. The uncertainty in the measured wire temperature is less than 2 $^{\circ}\text{C}$. The relative uncertainty of the heat transfer coefficient varies inversely with heat flux and is less than 10 % when $\Delta T > 12$ $^{\circ}\text{C}$, and less than 3 % during boiling.

Emulsions are prepared in batches of ~ 1.5 L. For each batch, distilled water is first degassed by boiling and then is cooled to the desired bulk temperature for the experiment.

The dispersed component is then added and emulsified in the water by pumping the fluid through a turbulent jet. The emulsified component is not degassed separately, and each batch of emulsion is used immediately after preparation. Long term stability of the emulsion is not necessary and therefore no surfactants are added to the emulsion. This approach avoids any confounding effects of surfactants on nucleation and boiling. The diameters of the FC-72 droplets produced by this method are measured using photomicrography and have $4 \leq d_d \leq 22 \mu\text{m}$. The average diameter is $8 \mu\text{m}$ and the volume-weighted average is $10 \mu\text{m}$. The droplet size is not normally distributed; the greatest number of droplets have $5 \leq d_d \leq 7 \mu\text{m}$ and less than ten percent have $d_d > 14 \mu\text{m}$. The average diameter does not depend on the volume fraction of the dispersed component, ϵ .

Experiments with emulsions of FC-72 are performed at two nominal bulk temperatures, 25 and 44 °C (31 and 12 °C of sub-cooling of the FC-72, respectively). Emulsions of pentane are tested at 24 °C only (12 °C of sub-cooling of the pentane). Emulsions are prepared with $\epsilon = 0.1, 0.2, 0.5, \text{ and } 1 \%$. Previous experiments have shown that for pool boiling of emulsions, the heat transfer coefficient depends on ϵ only up to $\sim 1 \%$ [4]. For experiments with emulsified FC-72, the heat flux from the wire is adjusted from zero to 2 MW/m², while for the emulsified pentane experiments heat flux up to 7.7 MW/m² is used. These ranges of heat flux encompass single phase natural convection, boiling of the dispersed component only, and boiling of the dispersed and continuous components. Burnout of the wire is observed only with emulsified pentane at heat flux greater than 4 MW/m².

3. Results

3.1. Water

Preliminary experiments are performed with distilled degassed water to ensure that the apparatus functions correctly (Fig. 2). The single-phase heat transfer coefficient is compared to the Morgan correlation [8] for horizontal circular cylinders,

$$Nu = 1.02Ra^{0.148}, \quad 10^{-2} < Ra < 10^2, \quad (1)$$

where the Nusselt and Rayleigh numbers are evaluated at the film temperature. The boiling heat transfer coefficient is compared to the Rohsenow correlation [9],

$$\frac{c_p (T_{wire} - T_{sat})}{i_{fg} Pr^s} = C_{sf} \left(\frac{q''}{\mu_f i_{fg}} \right)^{1/3} \left[\frac{\sigma}{g(\rho_f - \rho_g)} \right]^{1/6}, \quad (2)$$

where for copper surfaces in water $s = 1$ and $C_{sf} = 0.013$. The heat transfer coefficient is calculated from Eq. (2) by its usual definition, $h = q''/\Delta T$ where ΔT is the difference between the average wire temperature and the bulk fluid temperature. Experiments with water are performed at the same two bulk temperatures as the emulsions.

In the single phase region, the data differs from the Morgan correlation by less than 10 %, except at low power ($\Delta T < 20$ °C) where the experimental uncertainty is high. During boiling the wire temperature has large fluctuations that are not observed in the single phase region, and the surface temperature is slightly higher than that predicted by the Rohsenow correlation. Nevertheless these data indicate that the Morgan and the Rohsenow correlations describe the behavior of the apparatus reasonably well for $q'' < 2$ MW/m² for pure water. These correlations are therefore used as comparisons for the emulsion heat transfer data.

Another noteworthy behavior is that a surface temperature of ~ 145 °C is required to initiate boiling. Within a few seconds of the onset of boiling the surface temperature drops by ~ 20 °C. This high degree of superheat is a likely result of degassing the water before the tests. Degassing the water suppresses the accumulation of gas pockets at nucleation sites, thus suppressing the onset of boiling. Some dissolved gases are still present, as indicated by the fact that boiling begins at temperatures far below the superheat limit of water.

3.2. FC-72 in water

Heat transfer coefficients for the heated wire in dilute emulsions of FC-72 in water are shown in Fig. 3. Equations (1) and (2), computed using properties of water, are included

for comparison. Several interesting trends are apparent. First, the single-phase heat transfer coefficient is lower than for water, and the divergence from Eq. (1) grows larger with increasing ε and with increasing ΔT . In contrast, boiling heat transfer is enhanced compared to that for water (Eq. 2). The degree of superheat necessary to initiate boiling of the FC-72 is high, 35 to 50 °C. In some cases the wire temperature decreases after boiling begins, but the temperature change is small (< 4 °C) and occurs gradually as the heat flux increases. This loop in the boiling curve therefore has very different character from the sudden temperature drop observed at the onset of boiling in the water experiments. As ε increases, the loop becomes less pronounced (and is not present at all for $\varepsilon = 1.0$ %) and boiling begins at lower temperatures. At high heat flux (~ 2 MW/m²) there is also a trend towards boiling at lower temperatures with increasing ε . Another difference from the water experiments is that there are no significant fluctuations in the wire temperature during boiling.

3.3. Pentane in water

Because FC-72 in water emulsions require such a large degree of superheat to begin boiling, most of the boiling takes place at surface temperatures close to or above the saturation temperature of water. It is therefore difficult to separate the effects of the FC-72 boiling and boiling of the water. To address this issue experiments are performed using emulsions of pentane in water. Pentane has a saturation temperature of 35.9 °C at 1 atm, approximately twenty degrees lower than that of FC-72. Burnout of the wire occurs in only some of the experiments.

Figure 4 shows the heat transfer coefficient for pentane in water emulsions for $\varepsilon = 0.1$, 0.2, 0.5, and 1.0 %. These data have many features in common with those of the FC-72 in water emulsions. As expected, boiling occurs at surface temperatures approximately 20 °C lower than for the FC-72 in water emulsions. Just as in the FC-72 in water emulsions, the heat transfer coefficient for single phase free convection is always lower than for water and decreases with increasing pentane volume fraction.

The $\varepsilon = 0.5$ and 1 % pentane emulsions reach unusually high degrees of superheat before boiling (64 and 53 °C, respectively), and in these cases the wire temperature falls rapidly within five seconds of the onset of boiling (by 20 and 12 °C). This behavior is

similar to that observed in the water experiments. In contrast, the $\varepsilon = 0.2$ % pentane emulsion reaches a superheat of 46 °C, and after boiling begins the wire temperature decreases gradually by ~ 5 °C, similar to what is observed for the FC-72 emulsions. There is no loop at all in the boiling curve for the $\varepsilon = 0.1$ % pentane emulsion. This trend of increasing temperature overshoot before boiling with increasing ε is the reverse of that observed for the FC-72 emulsions.

At very high heat flux (~ 5 MW/m²) wire temperatures for $\varepsilon = 0.1, 0.2,$ and 0.5 % cases approach the same curve, approximately 15 °C below the temperature predicted by Eq. (2). It should be noted that, because such a high heat flux is not attained in the water experiments, it is not certain that Eq. (2) accurately describes the behavior of boiling water in this region. Therefore it is not claimed that the emulsion provides an improvement over boiling of water at very high heat flux. At lower heat fluxes however the pentane emulsions boil at lower temperatures than water.

The convergence to a common boiling curve at high heat flux is not observed for $\varepsilon = 1$ % because burnout of the wire occurs at $q'' = 4.02$ MW/m². For $\varepsilon = 0.2$ and 0.5 % burnout occurs at $q'' = 7.21$ and 6.19 MW/m² respectively. In the $\varepsilon = 0.1$ % case, a heat flux of 7.68 MW/m² is achieved without burnout. Thus there is a trend toward burnout at lower heat flux with increasing ε . In all three cases burnout occurs very close to one end of the heated wire and is likely influenced in part by the bus bar, rather than reflecting the behavior of the emulsion by itself.

Finally, fluctuations of the wire temperature are observed during boiling for $\varepsilon = 0.1$ %, and to a smaller extent for $\varepsilon = 0.5$ %. They occur only for $2.0 < q'' < 3.5$ MW/m². The reasons for these fluctuations and why they are not also observed in the $\varepsilon = 0.2$ and 1 % emulsions are not known. Sufficiently high heat fluxes are not attained with the FC-72 in water emulsions to determine whether this phenomenon exists in that system as well.

4. Discussion

The wide range of behaviors of the emulsions described in the previous sections defies easy, detailed explanation. However, some trends in the data can be identified that lend some insight into the physical processes that occur in heat transfer to dilute emulsions.

4.1. Single phase behavior

In the single phase portion of the experiments it is apparent that the presence of the dispersed component hinders natural convection heat transfer significantly. Some decrease in the heat transfer rate is expected because pentane and FC-72 both have much lower thermal conductivity than water (at 25 °C, $k = 0.595$, 0.117 , and 0.056 W/m-°C for water, pentane, and FC-72 respectively). However, according to the effective medium theory of Maxwell [10], at $\epsilon = 1$ % the effective conductivity of the emulsion can be no more than 1.5 % lower than that of water. The effect of the dispersed component on the viscosity of the mixture is similarly small [11]. The Rayleigh number for a dilute emulsion in single phase free convection is therefore close to what it would be for the continuous component alone, and the large decrease in single phase heat transfer coefficient is not a result of the behavior of the bulk of the emulsion. Instead it suggests that droplets of the dispersed component collect on the surface of the heated wire, and this conclusion is supported by visual evidence as well [7]. It is not possible to determine with the instruments used in this study to what extent the droplets wet the surface. If droplets coalesce and form a uniform layer on the wire surface, the layer need only be a few microns thick to cause the observed decrease in heat transfer.

4.2. Dispersed component boiling and enhanced continuous component boiling

As noted in Section 3.2, emulsions of FC-72 in water are observed to begin boiling close to the saturation temperature of water, so that it is difficult to separate the effects of boiling FC-72 droplets alone from evaporation of the water. In contrast, the boiling curves for emulsions of pentane in water have two distinct regions. At surface temperatures below ~105 °C only the pentane is boiling and the heat transfer coefficient increases moderately with surface temperature. This behavior is similar to that reported in previous studies [3]. At surface temperatures between 105 and 120 °C the heat transfer coefficient begins to increase rapidly. It is likely that this change corresponds to the point at which the water begins to boil as well. Boiling of the water would be enhanced by the bubbles of the dispersed component already present, and the presence of the bubbles of the dispersed component also eliminates the need for a large degree of superheat to initiate boiling of the continuous component.

With this in mind, it is reasonable to look for similarities between the FC-72 and pentane emulsion data, especially for $T_{\text{wire}} < \sim 105$ °C. In Fig. 5, the data for pentane emulsions and FC-72 emulsions with similar degree of subcooling are shown together. The data is plotted as a function of $T_{\text{wire}} - T_{\text{sat}}$, where T_{sat} refers to the dispersed component. This approach accounts for the differing saturation temperatures of FC-72 and pentane. It is immediately apparent that, neglecting the large temperature overshoot of the pentane emulsions, the boiling heat transfer coefficients of the two types of emulsions are remarkably similar as long as the wire temperature remains below ~ 105 °C ($T_{\text{wire}} - T_{\text{sat}} < 50$ °C). This result occurs despite the different thermophysical properties of the dispersed components. The enhanced boiling region in the FC-72 data can be clearly seen in heat transfer data for the $\varepsilon = 0.5$ and 1.0 % emulsions where the heat transfer coefficient suddenly rises rapidly above that of the pentane emulsions. The effect is not so pronounced for the $\varepsilon = 0.2$ % emulsions. This observed trend supports the idea that the presence of the bubbles of the dispersed phase enhances the boiling of the continuous phase. At larger dispersed phase volume fractions more bubbles are present [7], and significant boiling of the continuous component therefore begins at lower temperatures. However in the pentane data there are no clear trends with ε , either in the dispersed component boiling region or the enhanced continuous component boiling region.

4.3. Comparison to previous studies

Useful comparisons can be made between the data of this study and those of Bulanov et al. [3] who measure boiling heat transfer coefficients for several types of emulsions using heated wires in vertical and horizontal orientations. They test emulsions of R-113 in water and diethyl ether in water with similar degrees of subcooling as the emulsions used in this study. Because the wire used in this study has a different diameter and, in most cases, orientation than in [3], the single phase heat transfer coefficients in the two studies do not match. Therefore the effects of boiling are compared by examining the increase in heat transfer coefficient above the single phase value, $h - h_{1\text{ph}}$. For this purpose $h_{1\text{ph}}$ is taken as a constant value equal to the measured heat transfer coefficient shortly before boiling begins.

One important difference between the results of this study and those of Bulanov and co-workers [3,4] is found in the single phase heat transfer. Unlike the present study, they report little or no decrease in single phase heat transfer for emulsions. This result suggests that in their experiments there is no significant accumulation of the dispersed component on the heated wire. The use of platinum wires by Bulanov et al. (as compared to copper for the present study) may explain this discrepancy, due to the difference in surface properties of the two metals. Another possibly-significant difference is the difference in wire orientations. Most of the Bulanov et al. experiments use a wire in a vertical orientation, so that droplets of the emulsion would flow parallel to the wire surface. In the present study, in contrast, droplets are more likely to impinge on the horizontal heated wire as they rise past it. These results have implications for any model of boiling dilute emulsions that depends upon the behavior of droplets in the bulk of the emulsion rather than on the heated surface [2,5].

Interestingly, despite the difference in single phase behavior, boiling heat transfer coefficients reported by Bulanov et al. are quite similar to those of this study. Figure 6 shows heat transfer coefficients for emulsions of FC-72 in water and R-113 in water. The emulsions are sub-cooled by approximately the same amount (30 °C and 24 °C for FC-72 and R-113, respectively). The R-113 data of Bulanov et al. is for a vertical wire with 50 μm diameter and an emulsion with average droplet diameter of 60 μm . Despite the differences in droplet size, wire diameter and orientation, and dispersed component properties, the data are quite similar. The heat transfer coefficients for the $\varepsilon = 1$ and 2 % R-113 emulsions generally fall between those of the $\varepsilon = 0.5$ and 1.0 % FC-72 emulsions. The reason for the sudden jump in surface temperature for the $\varepsilon = 0.5$ % R-113 emulsion is not known.

Figure 7 shows heat transfer coefficients for emulsions of pentane in water and diethyl ether in water. Both types of emulsions are sub-cooled by only 12.5 °C. The diethyl ether data is for a horizontal wire with 50 μm diameter in an emulsion with average droplet diameter of 60 μm . The heat transfer coefficient for the diethyl ether is quite similar to that of the $\varepsilon = 1$ % pentane emulsion, and again this result occurs in spite of differences in dispersed component properties, wire diameter, droplet size and dispersed component

volume fraction. The largest difference between the two types of emulsions is that the diethyl ether emulsion does not exhibit any loop in its boiling curve.

The data suggest that the most important property of the dispersed component is its saturation temperature; differences in other thermophysical properties do not have a large influence on boiling heat transfer once boiling begins. The assertion that the heat transfer coefficient does not depend on ϵ above $\sim 1\%$ [4] is also borne out by these comparisons. There is more variability within the data of the present study for $0.1 \leq \epsilon \leq 1.0\%$ than there is difference between the data of this study and those of Bulanov et al. [3] for $0.5 \leq \epsilon \leq 5.5\%$. It is also noteworthy that the heat transfer coefficients in Fig. 6 are not close to those shown in Fig. 7. This result suggests that the degree of sub-cooling of the bulk of the emulsion is also an important factor.

4.4. Surface temperature overshoot

One striking difference between pentane and FC-72 emulsions in Figs. 3 and 4 is the large temperature overshoot that sometimes occurs before the pentane emulsions begin to boil. Such overshoots occur inconsistently throughout the experiments in this study, and no correlation with the degree of sub-cooling of the emulsion or ϵ is apparent. One clear distinction is that the largest temperature overshoots are seen in the pentane in water emulsion data, and in those cases the temperature of the wire drops suddenly after the inception of boiling. The inconsistent behavior suggests that temperature overshoots are linked to some aspect of the preparation of the emulsions that is not adequately controlled in this study.

One likely source of variability in the emulsions is in the degree to which they are degassed. As noted in Section 2, the water used in the emulsions is first degassed by boiling, but the dispersed component is not degassed separately. Additionally, after degassing the water is cooled to near room temperature and handled further in the course of producing the emulsion. This procedure provides opportunities for the water to re-absorb atmospheric gasses. The large degree of superheat required to initiate boiling in the water experiments (Fig. 2) suggests that the emulsions remained at least partially degassed, but differences in the handling of each batch of emulsion could lead to different amounts of dissolved gases in each experiment. A slight change in the configuration of the apparatus

used to produce the emulsions is also made for the pentane emulsions, as pentane is less dense than water (in contrast to FC-72, which is denser than water). It is noteworthy that none of the previous investigators of boiling in emulsions [1-4,12] mention degassing procedures in any of their experiments. In fact, Bulanov's theory of chain boiling [2] depends on the presence of dissolved atmospheric gases in the dispersed component. The data of the present study suggest that dissolved gases do not impact the boiling heat transfer coefficient, although there may be some influence on the initiation of boiling.

5. Conclusion

This paper presents the results of an experimental study of the pool boiling heat transfer of dilute emulsions. Two combinations of fluids are studied, pentane in water and FC-72 in water. In both cases the saturation temperature of the dispersed component is significantly lower than that of the continuous component. However in the case of FC-72 in water, the degree of superheat necessary to cause boiling of the FC-72 is high enough that boiling only occurs close to the saturation temperature of water. The data show two boiling regions, boiling of the dispersed component only and boiling of both the dispersed and continuous components.

A comparison of data for emulsions of different compositions, both from this study and from [3], suggests that for emulsions with $\epsilon > 1\%$ the improvement in heat transfer due to boiling of the dispersed component is independent of the heated surface geometry, ϵ , average droplet size in the emulsion, and thermophysical properties of the dispersed component. In contrast, the degree of superheat at the heated surface, sub-cooling of the bulk of the emulsion, and degree to which the emulsion is degassed are important factors. There is strong evidence that the dispersed component accumulates on the heated surface. However, the heat transfer data correspond closely to those of [3] in which such accumulation at the heated surface does not appear to occur.

The experimental data base yet seems to be too sparse to produce an overall correlation for heat transfer in boiling emulsions. The present data and the insights into the boiling processes discussed in part B of this paper [7] should contribute to the development of such a correlation.

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Figures and captions

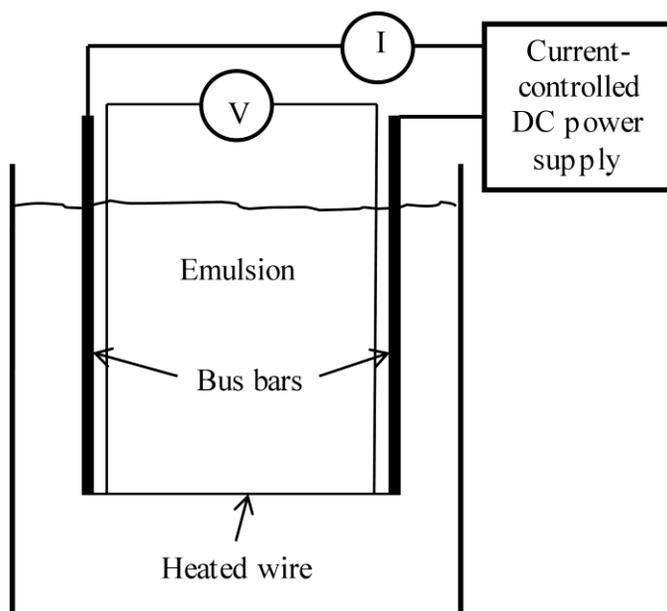
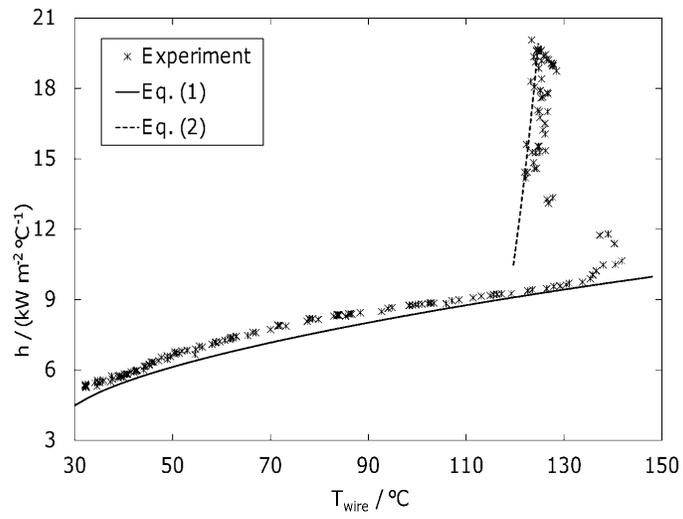
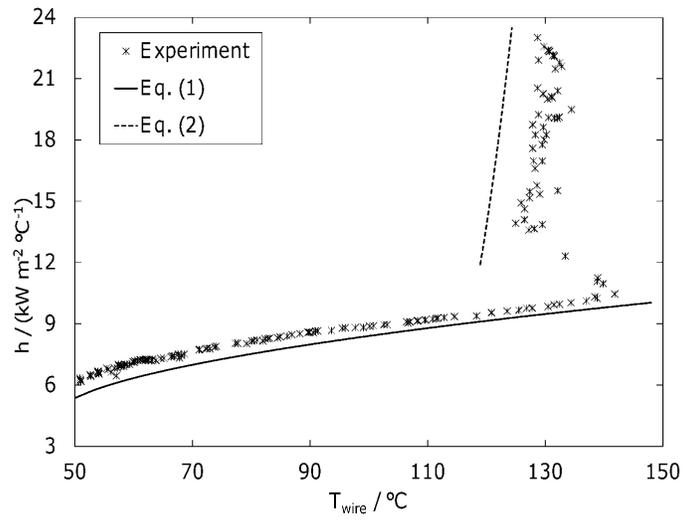


Figure 1. Apparatus.

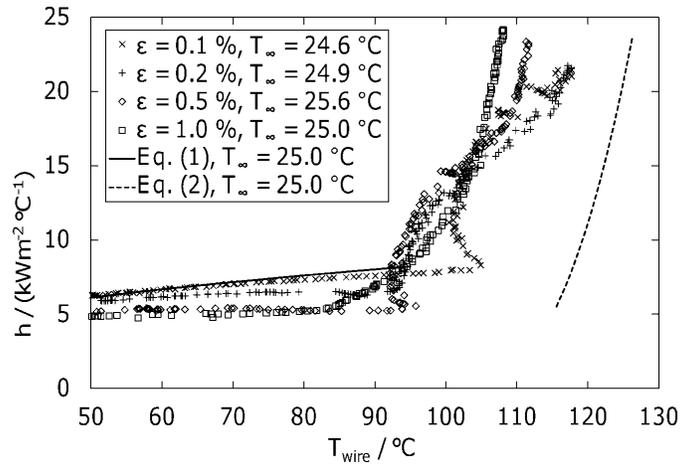


(a)

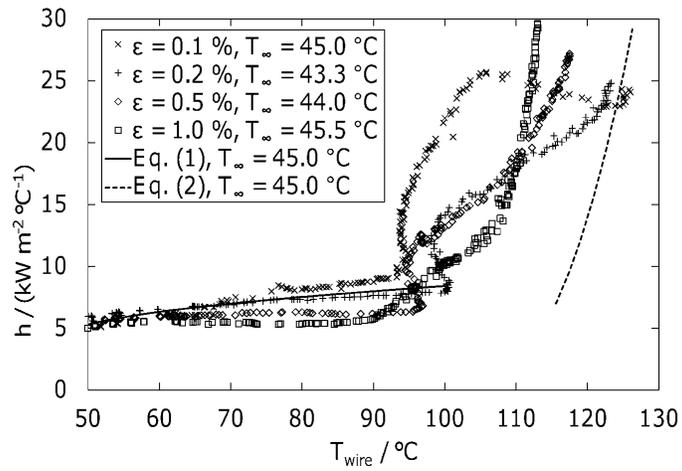


(b)

Figure 2. Free convection heat transfer coefficient from heated wire to water, (a) $T_\infty = 24.2$ $^\circ\text{C}$, (b) $T_\infty = 43.4$ $^\circ\text{C}$.



(a)



(b)

Figure 3. Free convection heat transfer coefficient for heated horizontal wire in emulsions of FC-72 in water with $T_\infty \approx$ (a) 25 °C and (b) 45 °C. Eq. (1) and (2) computed using properties of water.

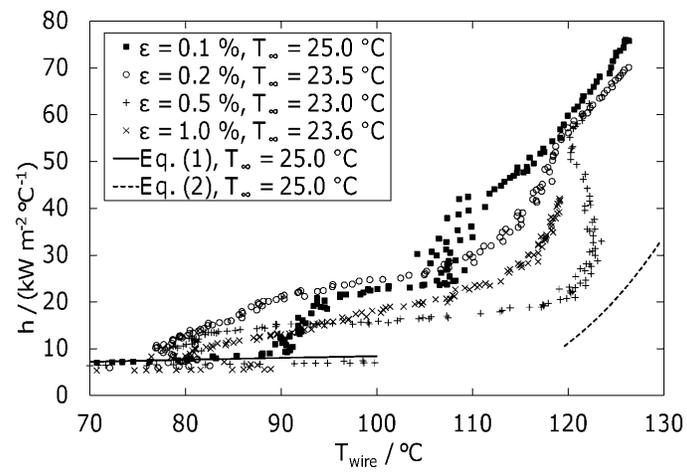
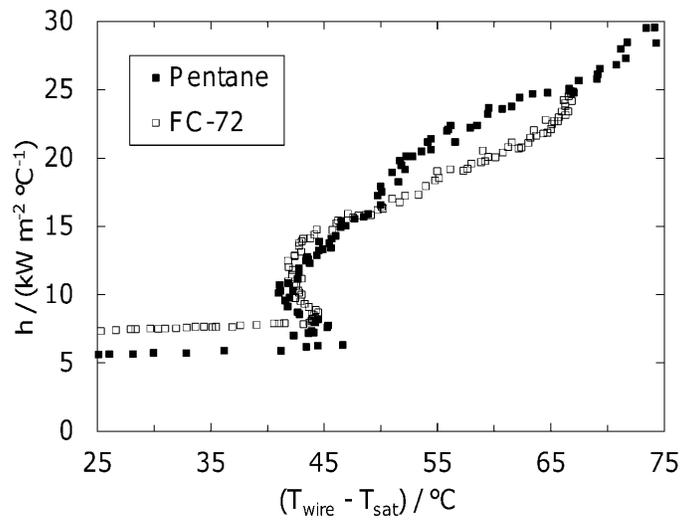
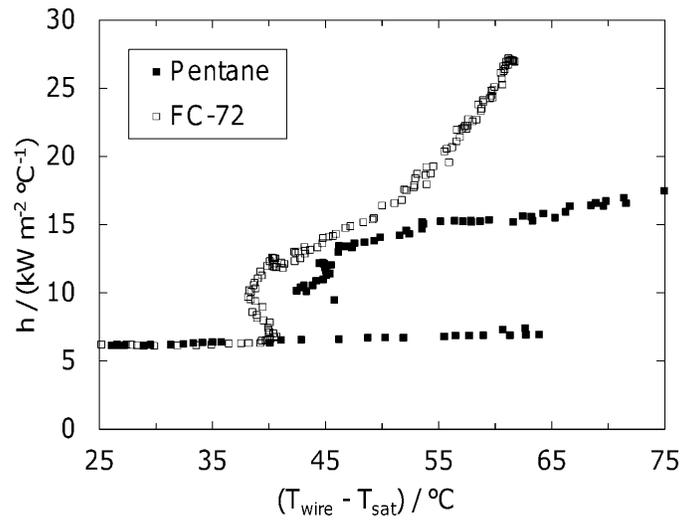


Figure 4. Free convection heat transfer coefficient for heated horizontal wire in emulsions of pentane in water. Eqs. (1) and (2) computed using properties of water.

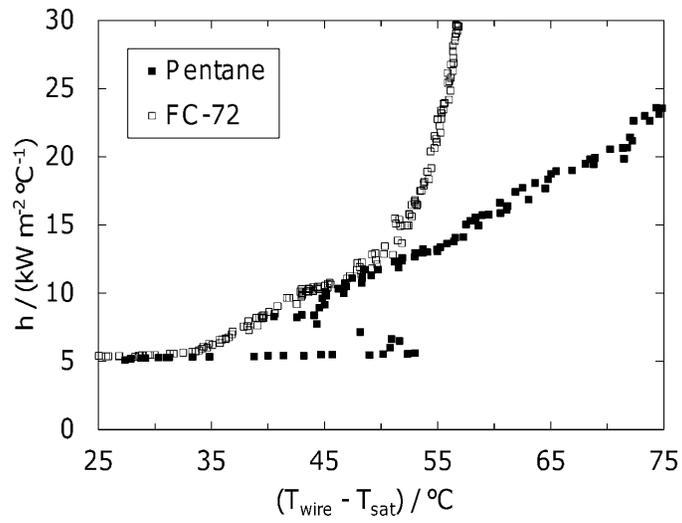


(a)



(b)

Figure 5. (caption below)



(c)

Figure 5. Comparison of boiling heat transfer coefficients for pentane in water emulsions and FC-72 in water emulsions with $\varepsilon =$ (a) 0.2 %, (b) 0.5 %, and (c) 1.0 %.

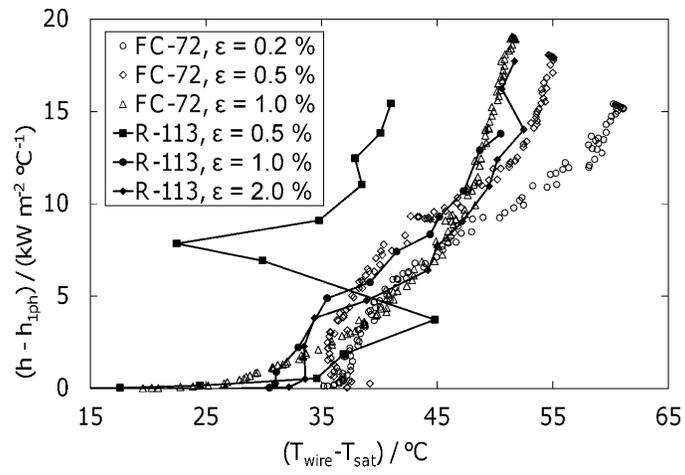


Figure 6. Comparison of boiling heat transfer coefficients for FC-72 in water emulsions (this study) and R-113 in water emulsions [3].

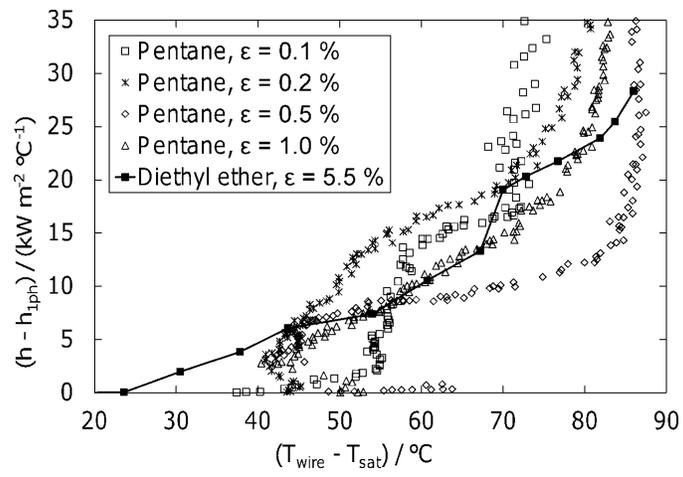


Figure 7. Comparison of boiling heat transfer coefficients for pentane in water emulsions (this study) and diethyl ether in water emulsions [3].