An experimental study of boiling in dilute emulsions, part B: Visualization

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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 data for single phase convection, boiling of the dispersed component, and enhanced boiling of the continuous component are correlated with images of the emulsion near the heated surface. Large bubbles are observed to form on the heated surface and remain attached to the surface. There is evidence of boiling of individual droplets that do not contact the heated surface under some circumstances. For very dilute emulsions and at moderate heat flux the attached bubbles are the dominant boiling mode.

Key words: emulsion, heat transfer, boiling, visualization

Nomenclature

C_{sf}	Surface-fluid parameter in Eq. (2)
c_p	Constant-pressure specific heat, kJ/kg-°C
d	Diameter, m
f	Frequency, Hz
g	Gravitational force, N/kg
h	Heat transfer coefficient, W/m^2-°C
i	Specific enthalpy, J/kg
k	Thermal conductivity, W/m-°C
Nu	Nusselt number, hd_{wire}/k
Pr	Prandtl number, ν/α

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q''	Heat flux, W/m^2
R	Droplet or bubble radius, m
Ra	Rayleigh number, $\frac{g\beta_{film}\left(T_{wire}-T_{\infty}\right)d_{wire}^{3}}{\nu_{film}^{2}}\mathrm{Pr}_{film}$
s	Prandtl number factor in Eq. (2)
T	Temperature, K

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

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

1. Introduction

One of the major hindrances to understanding the behavior of boiling emulsions is their opaque nature, which makes visual observation of the boiling emulsion very difficult. A number of experimental studies have been performed that report only heat transfer data and are discussed in more detail in [1]. In contrast only one published study incorporates visual observation as well as heat transfer data [2]. Mori et al. are able to obtain images of boiling on a heated wire by restricting the emulsion to a very thin layer (~1 mm thick) and using emulsions with large droplet sizes and moderate dispersed component volume fraction. They are able to obtain images of boiling near the heated surface at moderate heat fluxes shortly after the inception of boiling and only for $0.1 \leq \varepsilon \leq 0.2$ %. Using a high-speed camera (up to 5000 frames/second), they are able to observe the motion of individual droplets in the emulsion. They observe boiling of individual droplets close to (but not contacting) the heated surface, as well as boiling at locations on the heated surface where the dispersed component has collected. The relative amount of each type of boiling varies with the composition of the emulsion, which they attribute to changes in the relative wettability of the heated wire by the two components of the emulsion. Dissolved air in the emulsion and the degree of subcooling of the bulk of the emulsion are also described as playing a role in the boiling behavior of the emulsion. Images included in [2] show one case in which several bubbles accumulate on the heated surface and one in which bubbles do not appear to remain attached to the surface.

This paper reports the results of an experimental study of the behavior of boiling dilute emulsions, including visual observations correlated with heat transfer data. Details of the test apparatus and procedures are given in part A of this study [3]. A video camera is used to record images of the boiling emulsion with a resolution of 4.5 μm per pixel at a rate of 30 frames/s. Images of boiling water are also obtained using the same apparatus for comparison. The camera used is an Edmund Optics model number EO-1312M with a Navitar Zoom 7000 macro zoom lens. A short exposure time (~100 μs) is used to capture rapid motion of bubbles, but the rolling shutter of the camera causes image artifacts for fast-moving objects.

It is not possible to observe individual droplets using this imaging system due partially to the small size of the droplets ($4 \leq d_d \leq 22$ μm, average $d_d \approx 8$ μm), although bubbles with $d_b \approx 20$ μm are visible. An additional difficulty in observing droplets is the small difference in index of refraction between the components of the emulsions (FC-72 in water and pentane in water). Because all the fluids used in this study are transparent, droplets and bubbles are visible only due to refraction or reflection of light at their surfaces. Both FC-72 and pentane have indices of refraction close to that of water (~ 1.3). The index of refraction of their vapors is essentially unity, and thus bubbles are much more visible than droplets.

2. Results

Preliminary experiments are performed with distilled degassed water to ensure that the apparatus functions correctly. These experiments show that the single-phase heat transfer coefficient is close to the Morgan correlation [4] for horizontal circular cylinders,

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

In Eq. (1), the Nusselt and Rayleigh numbers are evaluated at the film temperature, $(T_{wire} + T_{\infty})/2$. For $q'' < 2.5$ MW/m^2, the boiling heat transfer coefficient is comparable to values given by the Rohsenow correlation [5],

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

where $C_{sf} = 0.013$ and $s = 1$ for copper surfaces in water. The heat transfer coefficient is calculated from Eq. (2) by its usual definition, $h = q''/(T_{wire} - T_{\infty})$. These correlations are used to compare the behavior of the emulsions to that of water.

2.1. Boiling water

Figure 1 shows several images of the heated wire from a boiling water experiment. The boiling curve for the same experiment is shown in Fig. 2, and the conditions at which the images are recorded are noted. For this experiment there is little contrast between bubbles in the field of view and the surrounding water, so the contrast of the images in Fig. 1 has been digitally enhanced. The increased contrast causes the grainy appearance of some images and lack of detail in the wire itself, which is bright enough to wash out the sensor. The small bright circle at the center of each bubble is a reflection of the light source around the camera lens.

Heat transfer behavior of the heated wire is much the same as the water experiments reported in [3]. As before, the heat transfer coefficient in the single phase region is slightly higher than predicted by Eq. (1), and the boiling heat transfer coefficient is quite close to that given by Eq. (2). Some interesting transient behavior is observed during boiling at moderate heat flux. Shortly after boiling begins (point a in Fig. 2, $q'' \approx 1.05$ MW/m^2), the temperature of the wire is ~6 °C greater than that predicted by Eq. (2), but as the heat flux is held constant for several seconds the wire temperature decreases to within 2 °C of Eq. (2). When the heat flux is adjusted upwards and again held constant, the same behavior is observed again although to a lesser extent. This behavior does not occur at higher heat fluxes. It is most likely the consequence of a delay in the initial activation of nucleation sites on the heated wire.

The first sign of boiling is a sudden increase in the heat transfer coefficient above the value predicted by Eq. (1), which corresponds to the sudden appearance of bubbles on the heated wire (Fig 1a). Before this point there is no visible activity at the heated wire. The bubbles initially remain attached to the heated wire and their locations and diameters are essentially steady. As the heat flux dissipated by the wire increases, the bubbles slowly grow larger and some begin to detach from the wire (Fig. 1b). The bubbles depart from the wire with increasing frequency with increasing heat flux. This behavior is the generally expected behavior for subcooled boiling in pure liquids [6]. The size of the bubbles can be taken as an indication of the limits of the region in the thermal boundary layer around the wire where $T > T_{sat}$. Because the water is highly subcooled in the present experiments, this region is quite small.

At higher heat flux ($q'' > 1.7$ MW/m^2) the vapor bubbles grow quickly enough that some artifacts become visible in the images. In Fig. 1c, the arrow indicates a portion of a bubble that forms while the image is being recorded. In this experiment, the camera is oriented such that the image sensor scans rows of pixels left-to-right. As heat flux approaches 2 MW/m^2 the wire begins to vibrate intermittently, which manifests as waviness in the recorded images (Fig. 1d). The wire vibrates at approximately 270 Hz with a maximum magnitude of ~45 μm. The vibration does not have any apparent effect on the heat transfer from the wire, and is probably caused by the rapid growth and departure of bubbles at the wire.

2.2. FC-72 in water emulsion

Figure 3 shows several images of boiling on the heated wire in an emulsion of FC-72 in water with $\varepsilon = 0.1$ %. Figure 4 is the boiling curve for the same experiment. The bulk temperature of the emulsion is 35 °C, midway between the bulk temperatures of the FC-72 experiments reported in the first part of this paper. In general the heat transfer coefficients for this experiment falls between those of the two earlier experiments. In particular, the rather sudden increase in surface temperature at high heat flux reported for the $T_\infty = 45$ °C case in [3] also occurs here but is smaller in magnitude and somewhat more gradual.

The images recorded in this experiment bear many similarities to those recorded of boiling water. Bubbles first become visible on the heated wire at the same time that the heat transfer data shows the first sign of boiling (Fig. 3a). As heat flux increases more bubbles form, grow larger (Fig 3b), and detach from the wire with increasing frequency. One interesting behavior observed in this experiment is that some bubbles depart the wire with significant velocity. Figure 3c shows a bubble initially attached to the side of the wire closest to the camera that travels downward after departing from the wire before rising in front of the wire due to buoyancy. As the bubble nears the top of the frame it shrinks visibly due to condensation. This rapid departure of bubbles from the wire is likely responsible for the vibration in the wire noted in Fig. 1d, although the rapid departure of a single bubble observed here does not cause any visible motion of the wire.

At high heat flux there are no large bubbles attached to the wire, although some small bubbles are observed to nucleate on the wire and then depart (Fig. 3d). Owing to the high temperature of the wire, it is likely that bubbles at the wire contain a mixture of FC-72 vapor and water vapor, but due to the very large subcooling of the water component, detached bubbles must contain only FC-72 vapor. Figure 3d also shows several small bubbles not in contact with the wire. The dispersed bubbles have $50 < d_b < 100$ μm, and so could be the result of boiling of individual FC-72 droplets with $10 < d_d < 20$ μm within the thermal boundary layer. However, as is seen in the second frame of Fig. 3d, some bubbles that nucleate on the wire surface are still propelled downwards from the wire, so the dispersed bubbles seen throughout the frame could be the result of this process as well. (The elongation of the bubble in the second frame is an artifact of the rolling shutter in the camera and indicates rapid downward movement.)

It is noteworthy that Fig. 3d appears to show very little boiling taking place, even though the heat flux and wire temperature are at their highest levels for this particular experiment. This behavior is similar to that of water boiling at high heat flux (Fig. 1d). And, similar to the water experiment, the surface temperature is close to that predicted by Eq. (2), which suggests that water is boiling at this point with little participation by the FC-72. The few small bubbles that can be observed cannot account for the high boiling heat transfer coefficient.

Observation of boiling in an emulsion of FC-72 in water with $\varepsilon = 0.2$ % is attempted, but the heated wire is visible only when it is placed very close to the front wall of the test chamber. The proximity of the wire to the wall influences the heat transfer so that Eqs. (1) and (2) no longer provide a good comparison for the heat transfer data. Even so, the wire and bubbles on the wire are only marginally visible, and at high heat flux bubbles accumulate on the wall of the chamber and obscure the view of the wire completely.

Images obtained for boiling at moderate heat flux show many similar behaviors to the emulsion with $\varepsilon = 0.1$ %, although a greater number of bubbles are present. One interesting behavior in this experiment is that the large attached bubbles on the wire do not grow steadily but instead fluctuate in size. This behavior is probably due to coalescence, either of adjacent bubbles on the heated wire or of droplets in the boundary layer with the large bubbles. The bubbles are visible only while they are attached to the wire, so it is unknown whether significant numbers of detached bubbles ever form as in Fig. 3d.

2.3. Pentane in water emulsion

Figure 5 shows several images of the heated wire during boiling of an emulsion of pentane in water with $\varepsilon = 0.1$ %. The corresponding heat transfer data is shown in Fig. 6. At 20 °C the indexes of refraction of water, FC-72, and pentane are 1.333, 1.251, and 1.357, respectively. Because the difference in the indexes of refraction for pentane and water is smaller than for FC-72 and water, the emulsions of pentane are generally more transparent than the emulsions of FC-72.

Bubbles of pentane vapor first become visible on the heated wire at the onset of boiling (Fig. 5a), just as in the previous experiments. As heat flux increases, the bubbles grow larger and more bubbles form (Fig. 5b). Some oscillation in the size of these large bubbles is observed, similar to the $\varepsilon = 0.2$ % FC-72 experiment, but the fluctuations in this case are small. As the heat flux increases further the bubbles begin to depart from the wire. Bubbles depart with increasing frequency and at smaller sizes as the heat flux increases (Fig. 5c). At intermediate heat flux the wire temperature is observed to fluctuate by several degrees with a period of a few seconds. While this temperature fluctuation occurs, several small bubbles form on the wire and then depart simultaneously (Fig. 5d). The temperature fluctuations cease when the simultaneous departure of the bubbles ends (Fig. 5e). No reason for the simultaneous departure of the bubbles is observed. Similar temperature fluctuations are also observed for the $\varepsilon = 0.5$ % case over the same range of heat fluxes (see [3]).

At high heat flux ($q'' > 4$ MW/m^2), bubbles with $25 < d_b < 200$ μm can be observed attached to the wire as well as in the surrounding liquid (Fig. 5e). Boiling of individual droplets of pentane would produce bubbles with $24 < d_b < 130$ μm. The observed range of bubble diameters therefore indicates that some droplets boil individually, while the larger bubbles must be the result of coalescence. At the high surface temperatures that accompany these conditions the bubbles adjacent to the wire could also contain water vapor. The water in the emulsion is subcooled to such a great extent (~75 °C) that it is unlikely that water vapor bubbles could exist at any great distance from the wire, however. Some bubbles are observed below the heated wire in Fig. 5e, but a bubble can also be observed in the lower-left corner of the first frame moving rapidly downward, as indicated by the arrow. The bubbles below the wire therefore could also be due to bubbles being propelled off of the wire downward as was observed in the FC-72 in water emulsions (Fig. 3d).

Figures 7 and 8 show several images of the heated wire and heat transfer data for boiling in a pentane in water emulsion with $\varepsilon = 0.2$ %. The behaviors observed in this experiment are again similar to the previous experiments. The large bubbles that form on the wire at the inception of boiling tend to grow and shrink erratically, similar to the $\varepsilon = 0.2$ % FC-72 in water emulsion, but at a slow rate. In addition, small bubbles continually form and collapse again on the heated wire. It is not known whether the bubbles collapse entirely or merely shrink to too small a diameter to be observed against the heated wire. The disappearance of the bubbles could not be caused by their departure, as the velocity of the emulsion is not high enough to transport the bubbles out of the field of view between successive frames.

As the heat flux increases, bubbles begin to depart from the heated wire at increasing frequency and at smaller diameters. In some cases bubbles appear to briefly form small clusters without coalescing (Fig. 7a, b). At high heat flux the emulsion near the heated wire appears similar to the $\varepsilon = 0.1$ % pentane experiment (Fig. 7d), although the number density of bubbles is higher, which is to be expected if the bubbles form from pentane droplets. The range of bubble sizes in Fig. 7d is essentially the same as in Fig. 5e.

3. Discussion

As discussed in part A of this paper [3], the heat transfer data suggests that significant numbers of droplets of the dispersed component collect on the heated wire. The visual observations of the wire also support this conclusion. Each bubble that suddenly appears at the onset of boiling (Figs. 3a, 5a) is much larger than could result from a single droplet, suggesting that droplets coalesce before boiling begins. The fact that the bubbles grow from the wire surface also suggests that droplets collect there. The liquid required for the subsequent growth of the bubbles may come from a layer of the dispersed component on the wire or from collisions between the attached bubbles and dispersed droplets.

A fundamental feature of current models of boiling emulsions [1,7] is that the emulsified droplets boil within the thermal boundary layer without necessarily contacting the heated surface. However, the droplets of the emulsions used in these experiments have $4 < d_d < 22$ μm and, if they boil individually, would produce bubbles with $20 < d_b < 130$ μm. The images obtained of boiling emulsions at high heat flux (Figs. 3d, 5e, and 7a-d) show that the camera system used in the present experiments is capable of observing bubbles with diameters as small as ~ 25 μm. Therefore, while individual droplets cannot be seen, most bubbles that result from boiling droplets should be visible. However, it is quite clear from the images that at low heat flux and low dispersed component volume fractions there are no such small bubbles in the emulsion around the heated wire.

Instead of dispersed bubbles, at low heat flux large bubbles form on the wire and remain attached to it. The first appearance of the bubbles in the recorded video coincides with the sharp increase in the heat transfer coefficient that indicates the onset of boiling. The bubbles are observed to grow from the wire, most likely from nucleation sites that are wetted by the droplets that have collected on the wire. The bubbles of the dispersed component vapor can become much larger than the water vapor bubbles observed in the water experiment, most likely because the subcooling of the dispersed component of the emulsions is much smaller so that the region of liquid with $T > T_{sat}$ is larger.

Because these bubbles are mostly located above the wire (while the emulsion rises past the wire from below) and are stationary, they probably do not cause any significant disruption of the thermal boundary layer around the wire itself. Instead, the bubbles may increase heat transfer by fluid motion and phase change within each bubble, somewhat like a heat pipe. Each bubble on the wire grows due to evaporation at the base of the bubble until it grows out of the region where $T > T_{sat}$. Then, condensation near the top of the bubble balances evaporation at the base and the bubble reaches a stable size.

The same sequence of events is observed in each experiment with the emulsions: at the onset of boiling bubbles form on the wire and remain stationary. As heat flux increases the bubbles grow larger and eventually begin to detach from the wire. With further increases of heat flux, the bubbles depart at smaller diameters, until when high enough heat flux is attained, no bubbles are observed attached to the wire at all. At low heat flux these large attached bubbles are the dominant mode of boiling heat transfer. This mechanism of heat transfer enhancement appears to be much closer to what occurs in subcooled pool boiling of pure liquids than the hypothesized boiling of individual bubbles throughout the thermal boundary layer. It is not possible to define a clear bubble departure diameter for the bubbles that grow from the heated wire; as can be seen in Figs. 3c, 5c, and 7a-c, frequently small bubbles form and depart from the wire while larger bubbles remain attached to the wire.

For the FC-72 in water emulsion, the point at which bubbles begin to depart from the wire immediately rather than remaining attached coincides with an increase in the surface temperature. Similar behavior is observed in the pentane in water emulsions, where the surface temperature increases rather rapidly between $95 < T_{wire} < 105$ °C, and during this transition bubbles begin to depart from the wire more rapidly and at smaller diameters. However, for the pentane in water emulsions a significant number of dispersed bubbles are observed (Figs. 5e, 7d), whereas for the FC-72 in water emulsions at the same wire temperature there are hardly any (Fig. 3d), and the pentane in water emulsions have much higher heat transfer coefficients at the same wire temperatures.

Clearly, any model based on boiling of individual droplets around the heated surface is at best incomplete. However some small dispersed bubbles are observed in these experiments, and for the pentane in water emulsions, the small dispersed bubbles start forming at a lower surface temperature in the $\varepsilon = 0.2$ % case than in the $\varepsilon = 0.1$ % case. If that trend continues at higher dispersed component fractions (where video cannot be obtained), then boiling of dispersed droplets would be an important boiling mechanism for higher dispersed component fraction emulsions. For the 0.2 % pentane in water emulsion, many small dispersed bubbles are observed at wire temperatures below 100 °C, so they must indeed be pentane. And, in fact, the rate of boiling of individual droplets due to collisions with bubbles should increase very rapidly with increasing ε [1].

4. Conclusion

Results of an experimental study of boiling of dilute emulsions are reported. Behaviors observed in video recordings of the heated surface are correlated with the heat transfer data and shed light on the fundamental processes of boiling in dilute emulsions. Experiments are carried out with emulsions of pentane in water and FC-72 in water, two fluid combinations that have not previously been studied. These fluid combinations have properties closer to emulsions that would have practical use in high heat flux electronics cooling applications than the water in oil and oil in oil emulsions that have been the primary subjects of most previous studies.

The visualization experiments reveal the presence of large attached bubbles on the heated wire during boiling, which has not been previously reported. The formation of the bubbles coincides with the inception of boiling as seen in the heat transfer data. Also remarkable is the absence of any visual evidence of individual droplet boiling at very low dispersed component fractions and low temperatures. The large attached bubbles are the dominant mode of boiling heat transfer when few individual droplets boil. Images are obtained only for emulsions with $\varepsilon \leq 0.2$ %; it is possible that other boiling mechanisms, such as individual droplet boiling, may occur at higher dispersed phase volume fractions.

The only previous visual study of boiling emulsions [2] does not report any such large attached bubbles, although boiling of droplets due to contact with the heated surface is observed. This difference may be explained by the fact that they report results at only a single heat flux (and attached bubbles may have formed, unobserved, at lower heat flux), or the formation of such large bubbles may have been precluded by the very thin layer of emulsion present in their apparatus. Certainly the properties of emulsions make visual observations very difficult. An experimental method or apparatus that allows observation of emulsions of moderate dispersed phase volume fraction without influencing the heat transfer from a heated surface is a goal that has not yet been attained.

Further studies are required to understand the role of the large attached bubbles more fully. Specifically, detailed knowledge of heat transfer and flow within and surrounding the bubbles is important to understand how they enhance heat transfer. Methods of enhancing or suppressing the attached bubbles should be explored, including surface treatments for the heated surface. Surface features may also be responsible for enabling some large bubbles to remain attached to the wire while smaller bubbles form and depart. Surfactants, which would be necessary for long term stability of emulsions, also deserve further investigation. In fact, surfactants have been shown to have a negative effect on boiling heat transfer in emulsions under some conditions [8], but the mechanism by which they do so has not been determined.

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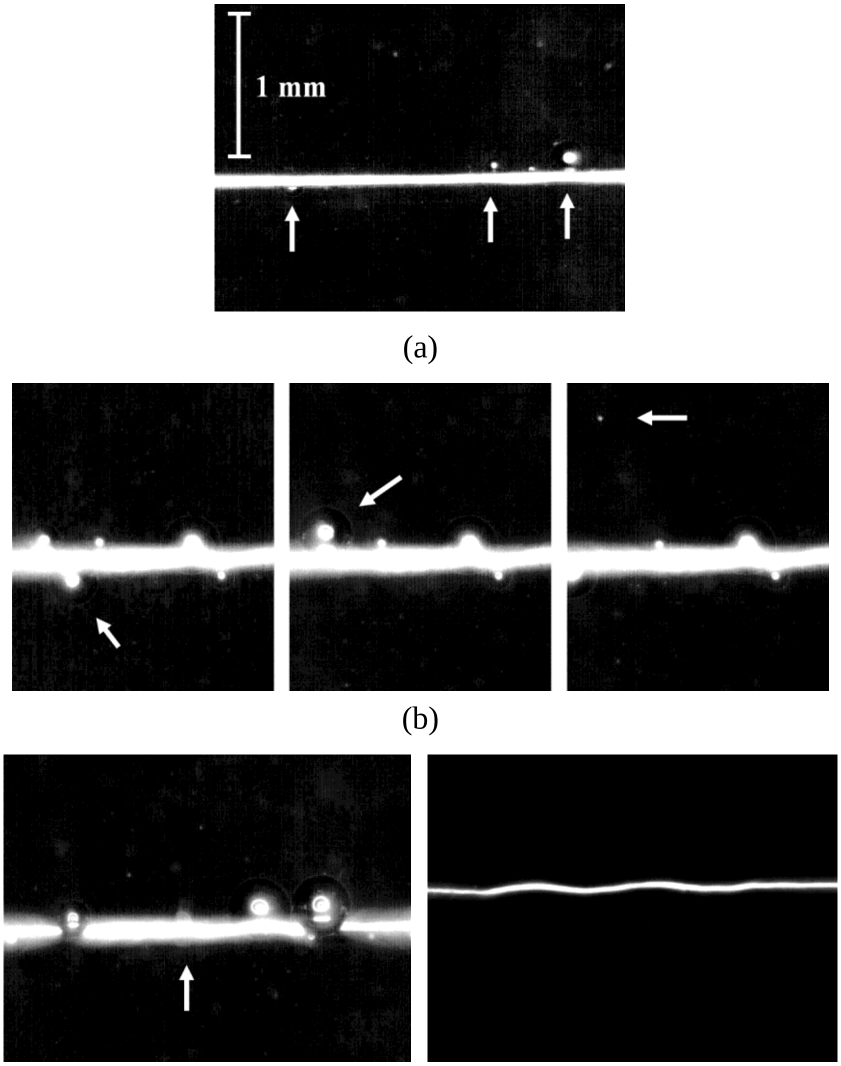
Figures and captions



(a)

(b)

(c) (d)

Figure 1. Images of heated wire during boiling in water, contrast enhanced to show bubbles. (a), onset of boiling, arrows indicate bubbles attached to wire. (b), sequence of three frames, arrows indicate bubble departing from the wire. (c), arrow indicates image artifact caused by rapid motion of bubble. (d), image artifact caused by vibration of wire, no bubbles visible.

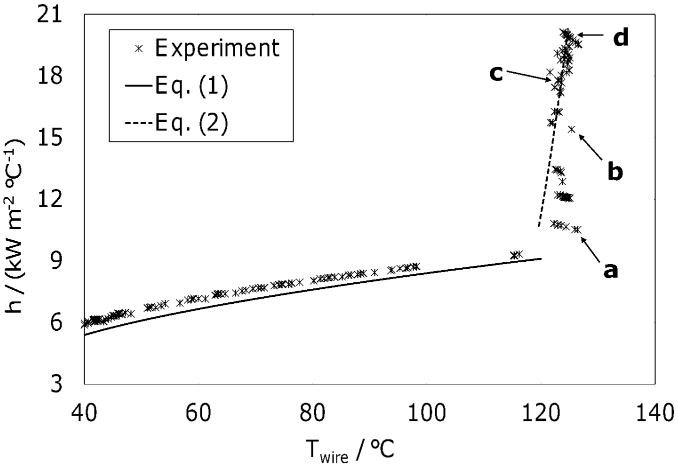
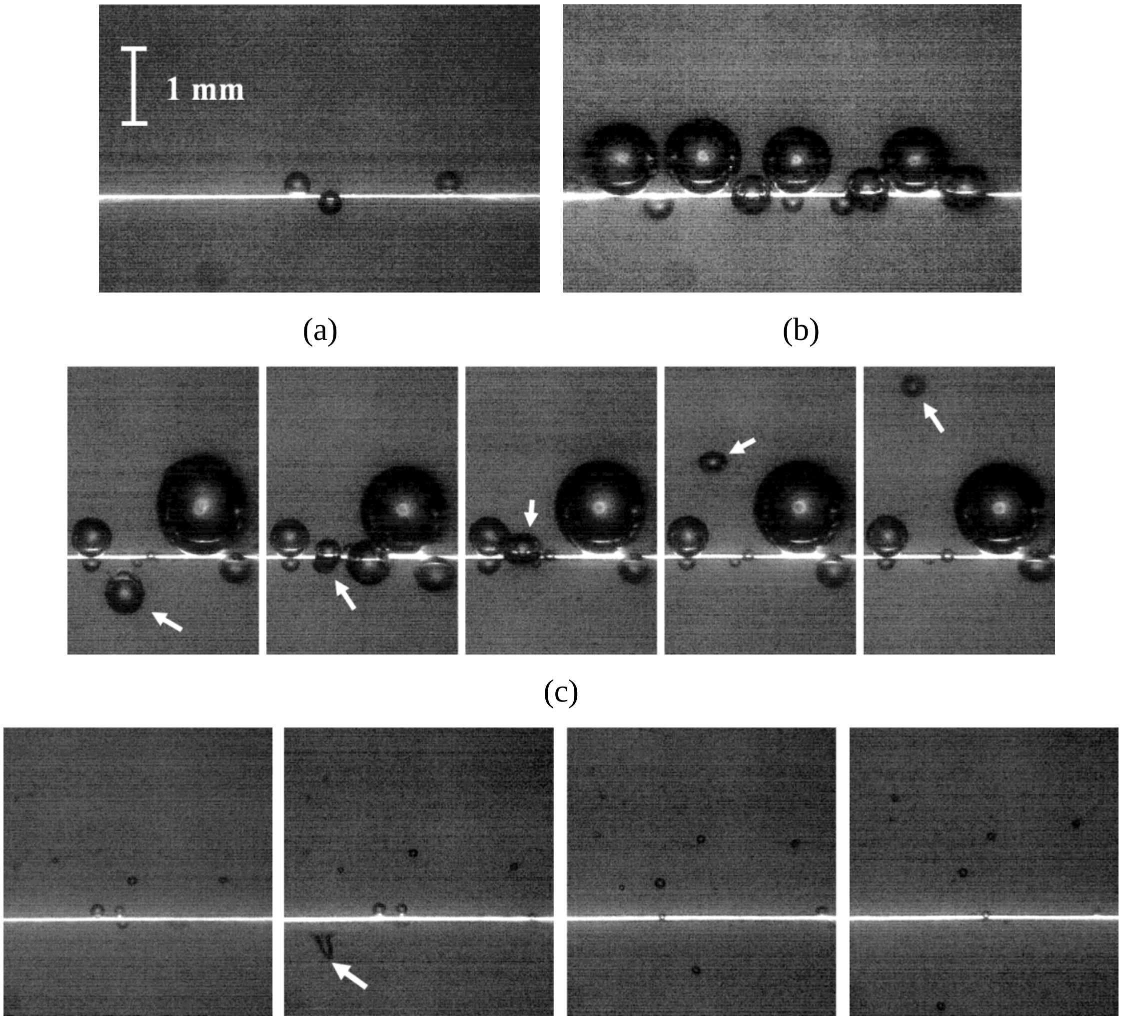


Figure 2. Free convection heat transfer coefficient from heated wire to water, T_∞ = 26.2 °C. Letters correspond to images in Fig. 1.



(a) (b)

(c)

(d)

Figure 3. Images of heated wire during boiling in FC-72 in water emulsion, $\varepsilon = 0.1$ %. (a), onset of boiling. (b), attached bubbles at higher heat flux. (c), arrow indicates bubble departing from wire. (d), boiling at high heat flux, arrow indicates downward-moving bubble.

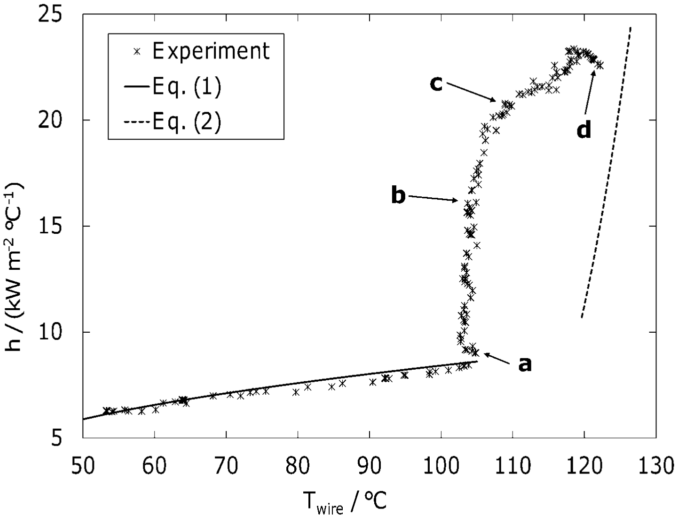
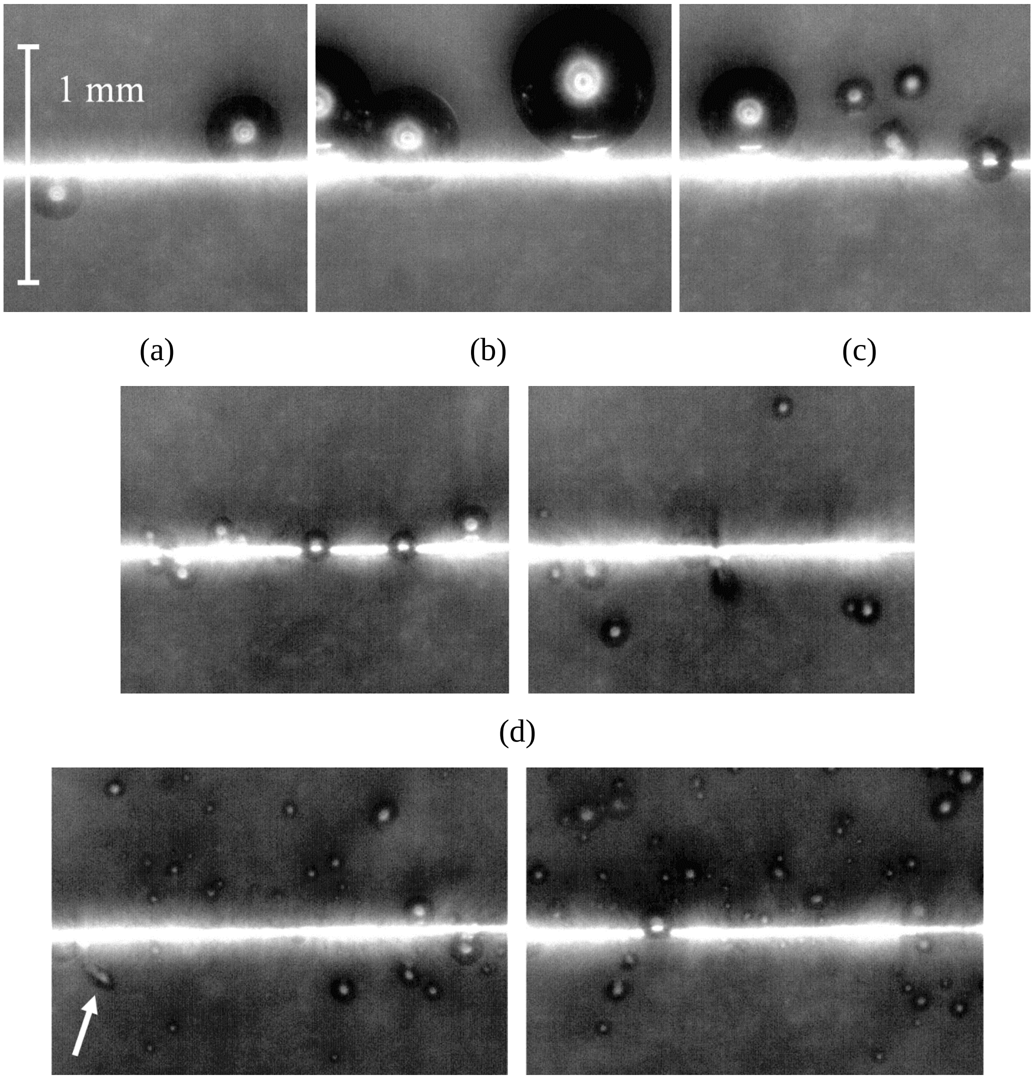


Figure 4. Heat transfer coefficient for heated wire to FC-72 in water emulsion, ε = 0.1 %, T_∞ = 35 °C. Letters correspond to images in Fig. 3. Correlations are calculated for water.



(a) (b) (c)

(d)

(e)

Figure 5. Images of heated wire during boiling in pentane in water emulsion with ε = 0.1 %. (a) and (b), large bubbles attached to wire. (c), departure of bubbles at higher heat flux. (d), simultaneous departure of bubbles. (e), boiling at high heat flux.

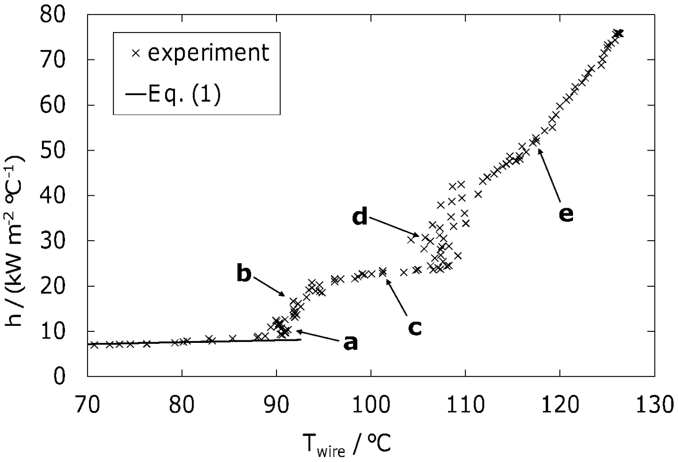
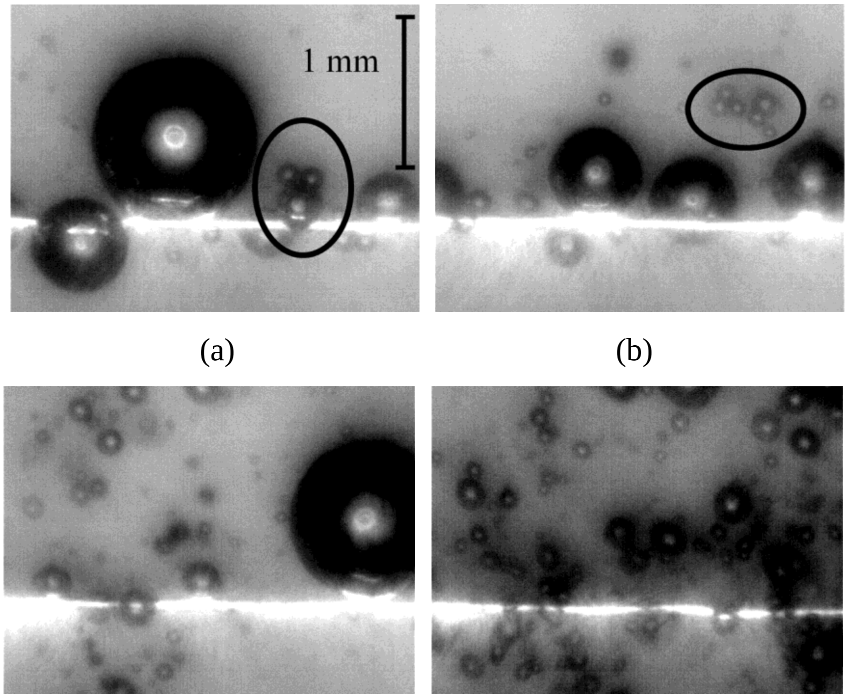


Figure 6. Heat transfer coefficient for heated horizontal wire in pentane in water emulsion, ε = 0.1 %, T_∞ = 25 °C. Letters denote images in Fig. 5. Equation (1) calculated using properties of water.



(a) (b)

(c) (d)

Figure 7. Images of heated wire during boiling in pentane in water emulsion, ε = 0.2 %. (a) – (d), boiling at increasing heat flux, circles indicate apparent clusters of bubbles.

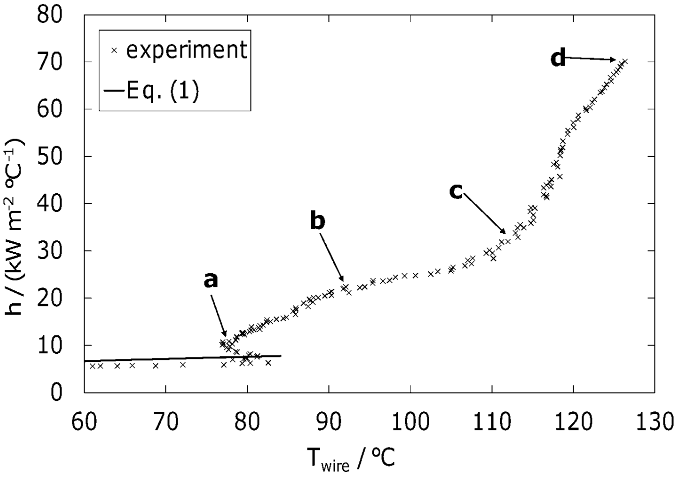


Figure 8. Heat transfer coefficient for heated horizontal wire in pentane in water emulsion, ε = 0.2 %, T_∞ = 23.5 °C. Letters denote images in Fig. 7. Equation (1) calculated using properties of water.