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# Saturated nucleate pool boiling bubble dynamics in aqueous drag-reducing polymer solutions

D. D. PAUL* and S. I. ABDEL-KHALIK
Department of Nuclear Engineering, University of Wisconsin-Madison, Madison, WI 53706, U.S.A.

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## INTRODUCTION

KOTCHAPHAKDEE and Williams [1] were the first to study nucleate pool boiling in aqueous drag-reducing polymer solutions. For aqueous solutions containing either polyacrylamide or hydroxyethyl cellulose boiling on a flat plate, they found that at a given temperature difference the nucleate boiling heat flux was substantially increased above that for pure water. Furthermore, they observed that the vapor bubbles produced in the polymer solutions were smaller than those produced in the pure solvent. They also observed that the frequency at which bubbles were produced was higher in the polymer solutions than for water boiling at the same heat flux on the same surface.

Miaw [2] attempted to verify these results by performing experiments with the same types of polymers boiling on a surface with artificially created nucleation sites. In order to allow photography of the heated surface, his studies were performed at extremely low heat fluxes near the onset of nucleate boiling. He was able to show that the bubbles produced in the polymer solutions were generally smaller and had higher emission frequencies than pure water boiling at the same nucleation site.

The objective of the present investigation is to compare the bubble dynamics of two dilute, aqueous, polymer solutions to those obtained with distilled water. These studies have been performed on a real boiling surface (i.e. no artificially produced nucleation sites), and at a heat flux intermediate between the onset of nucleate boiling and the critical heat flux. A horizontal, electrically heated platinum wire 0.30 mm in diameter and 30.0 mm long has been used. The wire is thin enough that bubbles completely envelop the wire as they grow. The statistically-averaged behavior of the bubble dynamics has been obtained by photographing the entire boiling surface using a high-speed movie camera. The average nucleation site density and the frequency distribution of bubble departure diameters have been measured and used to obtain the average bubble departure diameter, and the average waiting and growth periods during a bubble cycle. The fraction of the boiling heat flux attributed to latent heat transport has also been calculated.

The polymers tested are a polyacrylamide (Separan AP-30 manufactured by Dow Chemical Company), and a hydroxyethyl cellulose (Natrasol 250HHR manufactured by Hercules Inc.). The physical properties [3, 4] and rheological properties [5–7] of these polymers have been reported elsewhere. The concentrations of the polymer solutions, 9.5 wppm for the polyacrylamide and 55.8 wppm for the hydroxyethyl cellulose, used in this investigation correspond to a relative viscosity, $\eta_r$, of 1.08; this is low enough to insure that shear-thinning effects are negligible.

In addition to these two polymers, a polyethylene oxide (Aldrich Chemical Company No. 18946-4) and galactomannan polysaccharide (Galactasol 211 manufactured by Henkel Corp.) have also been tested [3]; the results of these experiments are not included since these two polymers precipitate from solutions under boiling conditions.

## EXPERIMENTAL RESULTS AND DISCUSSION

The experimental apparatus and procedure used in this investigation are identical to those reported earlier in our studies for water boiling along a heated platinum wire [8]. The boiling curves for these polymer solutions, i.e. plots of the boiling heat flux vs temperature difference, have also been reported in our earlier work [4].

In the present study, bubble dynamics have been photographed along the entire heated surface of the platinum wire at a saturated boiling heat flux of $0.358 \pm 0.006 \times 10^6$ W m$^{-2}$. Slow-motion films of the bubble dynamics have been analyzed to determine the average number density of active nucleation sites, and the frequency distribution of bubble departure diameters. From these quantities, the average bubble departure diameter; the average waiting and growth period of a bubble cycle; and the fraction of the boiling heat flux attributed to latent heat transport have been calculated.

### *Active nucleation site density*

Using slow-motion films of the entire boiling surface, an integrated, time-averaged, active nucleation site density $\langle N \rangle$ has been determined for distilled water and the two polymer solutions under the boiling conditions stated previously. A nucleation site is considered active as soon as a bubble appears on the heated surface and is considered inactive the moment the bubble departs from the surface. At the same boiling heat flux, the $\langle N \rangle$ values for the polyacrylamide and hydroxyethyl cellulose solutions are 270 and 330 sites m$^{-1}$, respectively; these are considerably lower than the water value of 405 sites m$^{-1}$. These differences are best explained by realizing that the addition of polymers to distilled water results in a unique fluid–surface interaction for each type of polymer. Both polymers have solution viscosities about 8% higher than distilled water, and the hydroxyethyl cellulose also lowers the solvent surface tension by about 5% [3].

### *Bubble departure diameter frequency distributions*

Using films of the entire boiling surface, the departure diameter for each bubble leaving the heated surface has been measured. If two bubbles combine before leaving the surface, their departure diameters are measured separately at the moment just before they combine. By taking these measurements over a known period of time, typically 1000 frames, a distribution of bubble departure diameters is obtained.

Figure 1 shows the frequency distribution of bubble departure diameters for pure water boiling at $0.352 \times 10^{-6}$ W m$^{-2}$. The histogram portion of the graph represents the actual experimental data. The curve drawn on the plot is a fitted asymptotic expansion of the normal frequency function $F(D)$ (see ref. [4]), defined such that $F(D)\,dD$ is the number of bubbles leaving the surface per nucleation site per unit time with diameters between $D$ and $D + dD$. Values of the average bubble departure frequency per nucleation site $\langle F \rangle$, the average bubble departure diameter $\langle D \rangle$, the standard

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* Present address: Battelle-Columbus Laboratories, Energy and Thermal Technology Section, 505 King Avenue, Columbus, OH 43201, U.S.A.

deviation of bubble departure diameters $\sigma_D$, the skewness coefficient $\gamma_1$, and the kurtosis coefficient $\gamma_2$ are given on each plot.

Figures 2 and 3 show the frequency distributions of bubble departure diameters for the polyacrylamide and the hydroxyethyl cellulose solutions, respectively. In both cases, the polymer solution's average bubble departure diameters ($\langle D\rangle = 1.19$ and 1.13 mm for the polyacrylamide and hydroxyethyl cellulose, respectively) are slightly smaller than that observed in pure water ($\langle D\rangle = 1.24$ mm). In addition, the polymer solution distributions are wider ($\sigma_D = 0.57$ mm) than the pure water case ($\sigma_D = 0.48$ mm). Perhaps the most striking comparison is the similarity in the shape of the two polymer solution distributions; both have skewness and kurtosis coefficients which are nearly identical ($\gamma_1 \simeq 1.27$ and $\gamma_2 \simeq 1.27$) and significantly different from the pure water values ($\gamma_1 = 0.72$ and $\gamma_2 = 0.13$). This shows that the effect of polymer additives is to shift the peak in the distribution curve towards smaller bubble diameters and correspondingly higher values of the departure frequency.

An attempt was made to compare statistically each polymer solution distribution to the pure water distribution using standard confidence limit procedures. However, these standard procedures are valid only for perfectly normal distributions ($\gamma_1 = \gamma_2 = 0$). In these cases, all of the distributions have positive skewness and kurtosis coefficients. These data have also been analyzed using a log-normal frequency distribution function, but the skewness coefficients ($\gamma_1 \simeq 0.3$ and $-0.2$ for the polymers and water, respectively) and kurtosis coefficients ($\gamma_2 \simeq -0.4$ and $-0.2$ for the polymers and water, respectively) were still significantly different from zero. For these reasons, only qualitative comparisons of the distributions are possible.

Values of the average bubble departure frequency per nucleation site, i.e. the area under the distribution curves, are given on each plot for pure water and the two different polymer solutions. Compared to pure water ($\langle F\rangle = 223$ bubbles $s^{-1}$), the average bubble departure frequency per nucleation site increased in the polyacrylamide ($\langle F\rangle = 249$ bubbles $s^{-1}$) and hydroxyethyl cellulose ($\langle F\rangle = 243$ bubbles $s^{-1}$) solutions. This is in agreement with the results of Miaw [2] and the observations of Kotchaphakdee and Williams [1] for the same types of polymers.

### *Average waiting and growth period*

By definition the average time period for a bubble cycle $\langle\theta\rangle$ is equal to the inverse of the average bubble departure frequency per nucleation site. This time period can be divided into the average waiting period $\langle\theta_w\rangle$ before a bubble begins to grow, and the average growth period $\langle\theta_g\rangle$ during which a bubble is in contact with the heated surface. Using the procedure outlined in ref. [8], values of the average growth and waiting periods were calculated for distilled water and the two polymer solutions.

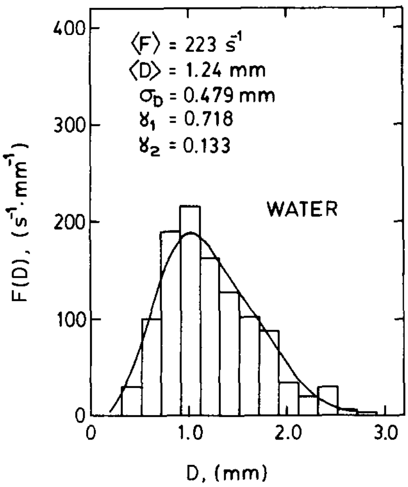

FIG. 1. The frequency distribution of bubble departure diameters for pure water boiling at a heat flux of $0.352 \times 10^6$ W $m^{-2}$.

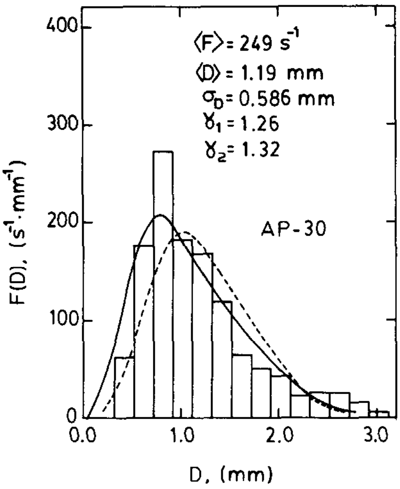

FIG. 2. The frequency distribution of bubble departure diameters for a polyacrylamide solution ($\eta_r = 1.08$) boiling at a heat flux of $0.364 \times 10^6$ W $m^{-2}$ (the dotted line is the corresponding distribution for pure water).

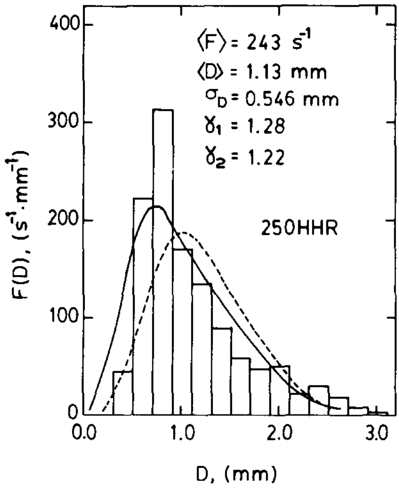

FIG. 3. The frequency distribution of bubble departure diameters for a hydroxyethyl cellulose solution ($\eta_r = 1.08$) boiling at a heat flux of $0.357 \times 10^6$ W $m^{-2}$ (the dotted line is the corresponding distribution for pure water).

The average waiting period corresponds to the time needed for the thermal boundary layer to build up to a level where bubble growth can be sustained. Compared to pure water ($\langle\theta_w\rangle = 2.72$ ms), the average waiting period increased slightly in both of the polymer solutions ($\langle\theta_w\rangle \simeq 2.94$ ms). The increase in the waiting period can be attributed in part to the decrease in the free convection heat transfer coefficient due to the increased viscosity ($\eta_r = 1.08$) of the polymer solutions.

The average growth time of a bubble cycle depends on the dynamics of the growth process. The forces acting on a bubble growing at a heated surface are inertia, buoyancy, frictional drag, and surface tension of the bubble in contact with the heated surface. Compared to pure water ($\langle\theta_g\rangle = 1.77$ ms), the average growth time is considerably shorter in both the polyacrylamide solution ($\langle \theta_g \rangle = 1.01$ ms) and the hydroxyethyl cellulose solution ($\langle \theta_g \rangle = 1.22$ ms). This necessarily implies that the bubble growth rate is substantially increased in the presence of drag-reducing polymer solutions. This result is in agreement with a theoretical model of bubble growth in a viscoelastic medium proposed by Street [9]. He represented the viscoelastic medium using the Oldroyd three-constant model and predicted that the initial bubble growth rate would be greater in a viscoelastic medium than in a Newtonian medium of the same viscosity.

*Fraction of heat flux due to latent heat transport*

Each bubble departing from the heated surface carries an amount of energy corresponding to the latent heat energy needed to produce the vapor associated with the bubble volume. From the number density of active nucleation sites and the frequency distribution of bubble departure diameters, the fraction of the boiling heat flux due to the latent heat transported by all of the vapor bubbles $\phi_{LH}$ has been calculated using the procedure outlined in ref. [8]. Compared to pure water ($\phi_{LH} = 0.56$), the fraction of the heat flux due to latent heat transport is considerably less in both the polyacrylamide solution ($\phi_{LH} = 0.46$) and the hydroxyethyl cellulose solution ($\phi_{LH} = 0.47$).

The difference between the boiling heat flux and the latent heat flux can be attributed to enhanced convection brought about by agitation and mixing caused by bubbles departing from the heated surface. The fact that the latent heat flux fraction is less in both the polyacrylamide and hydroxyethyl cellulose solutions when compared to pure water boiling at the same heat flux, necessarily implies that the agitation and mixing mechanism of these polymer solutions must be more efficient at transferring heat than the corresponding mechanisms in pure water.

## CONCLUSIONS AND SIGNIFICANCE

A practical method has been developed for correlating the nucleate boiling characteristics of a given fluid–surface combination. By measuring the average number density of active nucleation sites and the frequency distribution of bubble departure diameters, the following quantities have been determined: (1) the average bubble departure diameter, (2) the average bubble departure frequency per nucleation site, (3) the average waiting and growth period of a bubble cycle, and (4) the fraction of the boiling heat flux associated with latent heat transport. These parameters have been used to compare the boiling characteristics of two aqueous polymer solutions to those of distilled water.

Compared to pure water boiling at the same heat flux, the polyacrylamide and hydroxyethyl cellulose solutions have slightly smaller average bubble departure diameters and higher average bubble departure frequencies per nucleation site. The average waiting period of a bubble cycle, a measure of the time required for the thermal boundary layer to grow to a thickness sufficient for bubble growth, increased in these polymer solutions. At the same time, the average growth period of a bubble cycle decreased. Since the average bubble diameters are nearly identical in both the water and the polymer solutions, the decrease in the bubble growth period necessarily implies an increase in the bubble growth rates for the polyacrylamide and hydroxyethyl cellulose solutions.

When compared to boiling in distilled water at the same heat flux, the polyacrylamide and hydroxyethyl cellulose solutions also showed a substantial enhancement in that component of the boiling heat flux associated with agitation and mixing caused by vapor bubbles departing from the heater surface.

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