DROPWISE EVAPORATIVE COOLING: EFFECT OF DISSOLVED GASSES AND EFFECT OF SURFACTANTS

by

S. Tinker, di Marzo, M.
Mechanical Engineering Department
University of Maryland
College Park, MD 20742
and
P. Tartarini
Istituto di Fisica Tecnica
Universita di Bologna
Viale Risorgimento, 2
Bologna, Italy 40136
and
S. Chandra, and Y.M. Quiao
Mechanical Engineering Department
University of Toronto
Toronto, Ontario, M5S 1A4
Canada

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Dropwise Evaporative Cooling: Effect of Dissolved Gasses and Effect of Surfactants

S. Tinker*, M. di Marzo*, P. Tartarini^, S. Chandra+, Y.M. Quiao+

*Mechanical Engineering Department, University of Maryland, College Park, MD 20742
^Istituto di Fisica Tecnica, Universita' di Bologna, Viale Risorgimento, 2, Bologna, Italy 40136
+Mechanical Engineering Department, University of Toronto, Toronto, Ontario, Canada M5S 1A4

INTRODUCTION

This paper has three objectives: a) it summarizes the research program on dropwise evaporative cooling; b) it outlines the effect of dissolved gasses in the water droplets; and c) it provides insight into the effect of surfactants in the water droplets. There is only a minor effort devoted to the quantification of the droplet mass flux at the onset of flooding conditions which is not included here. Otherwise, this is a comprehensive review of all the findings that punctuated the cooperative research between the Buildings and Fire Research Laboratory of the National Institute of Standards and Technology (BFRL-NIST) and the Mechanical Engineering Department of the University of Maryland at College Park (UMCP).

Research Program Summary. In order to provide an organized overview of the publications that report the various findings of the research program, a topical organization is used rather than a chronological list of the archival publications.

The first set of studies [1,2] focusses on a single droplet deposited on a high thermal conductivity solid heated by conduction from below. The objectives are: a) to determine the accuracy of a conduction heat transfer model for the deposited droplet; and b) to finalize the liquid-vapor heat and mass transfer boundary condition.

This initial work is extended to include solids with low thermal conductivity. This extension requires the introduction of the implicit coupling of the liquid and the solid whereas in the high thermal conductivity case the two could be treated separately. Experimentally, this allows the development of an infrared thermographic technique to continuously monitor the transient behavior of the solid surface [3]. On the modelling aspect, a mixed numerical method, using boundary elements for the solid and a control-volume scheme for the liquid, is successfully implemented [4,5]. The validated results of the model confirm that: a) the liquid conduction treatment is adequate; and b) it is reasonable to further simplify the liquid treatment by considering conduction to be only one-dimensional (in the direction orthogonal to the surface). Further comparisons of the results with approximate closed-form solutions lay the foundation for the multi-droplet model [6].

In order to better approximate an actual fire environment, the heat input by conduction from below the solid is substituted by radiant heat input from above the solid surface. The experimental infrared thermographic technique is modified for this novel set up [7]. The direct radiation from above has a strong effect on the droplet configuration on the surface: the heat input at the liquid-vapor interface relaxes the surface tension and the droplet

spread on the surface increases. The combination of the direct radiation and of the increased spreading enhances evaporation while the reduction of the heat input by conduction at the liquid-solid interface depresses the evaporative phenomena. The comparable magnitude of these two effects yields evaporation times of the same order of the ones for the simple conduction case. The model is modified to incorporate the effect of direct radiation on the water droplet evaporation [8]. A simplified approach, based on the one-dimensional treatment of conduction in the liquid, is also very effective in limiting the computational time [9].

With this background information, the final objective of the program is pursued: the study of the thermal effect of a sparse spray. The experimental set up is modified to incorporate a controlled supply of water droplets (size, frequency and distribution) [10]. It is found that the mass flux does not correlate with the cooling effect in a systematic way. On the other hand, the substrate (i.e. the solid thermal properties) plays a significant role. A preliminary scheme for the treatment of the spray is proposed [11]. Last year, at this meeting, the complete model and the results were presented [12]. A manuscript for archival journal publication is currently in preparation. The model utilizes a modified closed-form solution with input from the single droplet models previously described. The results are in good agreement with the data. In the following, the last two topics of this review (i.e. the effect of dissolved gasses and of surfactants) are dealt with more extensively. Two separate papers have been written and are now under review for publication.

EFFECT OF DISSOLVED GASSES

Experiments The experimental set up is identical to the one used for the multi-droplet studies [10]. The droplet dispenser provides a controlled droplet distribution on the surface. An average droplet size of 10 ± 1 μL is obtained with frequencies as high as one Hertz. Experiments are run at initial surface temperatures of approximately 110 °C, 130 °C, 150 °C, 160 °C, and 180 °C. At each initial surface temperature, three mass fluxes of deionized water containing dissolved gases are tested. Over these of experiments, the mass flux of water ranges from 0.24 g/m^{2}s to 1.6 g/m^{2}s. At the higher mass fluxes, the surface is nearing the flooding conditions. The lowest four initial surface temperatures correspond to evaporative cooling, while the highest temperature corresponds to full nucleate boiling regime for water on a solid surface made of the Macor, a glass-like material.

The data processing and reduction for the experiments follow the same procedure adopted by Dawson [10] in his spray cooling experiments using degassed water. To determine the transient average surface temperatures, frames of a recorded experimental run are digitized at 30-second intervals. There are 130 shades of gray associated with the infrared intensity levels. Since the temperature range is of 100 °C, the temperature resolution is 0.77 °C/ gray shade. The pixels contained in the total viewed area are 512 by 480 in the horizontal and vertical direction, respectively. The average spatial resolution is 0.00013 meters/pixel.

Results and Discussion Graphical results of the transient average surface temperature are shown in Figs. 1 and 2. The raw data are shown for both the experiments using: a) water containing dissolved gases; and b) degassed water [10]. The general trend apparent in each plot for both the degassed and dissolved gases data is the decay of the average surface

temperature from its initial value to some steady state value. The deviation of the data points from a smooth decay occurs due to the nature of the data acquisition. Since only a portion of the sprayed area is viewed and averaged, at any instant, the number of droplets that are in the field of view may be different than at other instants thus resulting in oscillations of the average surface temperature. An exponential fit is used to curve-fit all the data representing the transient behavior of the average solid surface temperature.

Examination of the results suggests that the dissolved gasses enhance the heat transfer from the surface by decreasing the incoming radiant input and, therefore, achieving a lower steady state temperature. To quantify this effect, one should attempt to relate the variation in the final steady state temperature to the temperature excursion present in the degassed water results. Two major effects must be included in the characterization of a given transient: a) ΔT, the solid surface temperature drop; and θ, the difference between the initial solid surface temperature at the onset of nucleate boiling and the actual initial solid surface temperature. These quantities are related the radiant heat input and the water mass flux. One could suggest to identify, as independent variable, the ratio of these two quantities while retaining the temperature variation as the dependent variable. In order to compensate for the large variation in this independent variable, one could plot the temperature variation versus the logarithm of the ratio $\Delta T / \theta$ as shown in Fig. 3. This analysis would indicate that the effect of dissolved gasses decreases as the values of the ratio $\Delta T / \theta$ increases. This ratio is large for large temperature drops and for initial solid surface temperatures near the onset of nucleate boiling conditions for degassed water.

EFFECT OF SURFACTANTS

Experiments and Computations Liquid surface tension and solid-liquid contact angle are reduced by dissolving Sodium Dodecyl Sulfate in water. Three surfactant concentrations are used: 0 ppm (pure water), 100 ppm and 1000 ppm. A droplet diameter of about 2 mm is used for all cases. The droplet is released from 50 mm above the surface resulting in an impact velocity of 1 m/s. The surface is made of stainless steel and it is square in shape with 50.8 mm sides and 6.35 mm thickness. It is heated from below by conduction. The model for single droplet evaporation [5,8] is used to predict the experimental data and to gain confidence in the correct representation of the physical phenomena. The comparisons are shown in Figs. 4,5, and 6. The agreement is excellent.

Results and Discussion The droplet volume evolution is reported in Fig. 4 for the three different concentration of surfactant at the same initial solid surface temperature of 80°C. As the concentration of surfactant increases, the initial droplet spreading on the surface increases. This causes the droplet evaporation to start at a faster rate.

The temporal behavior of the contact angle is presented in Fig. 5, and the droplet diameter evolution is shown in Fig. 6. Both these figures provide a representation of the transient droplet shape. In particular, the point at which the receding angle is reached is clearly noticeable. At this angle, the solid-liquid contact surface starts to shrink. In general, these results indicate the surfactant enhances the heat transfer rate. This effect is analogous to the effect of direct thermal radiation [7].

SUMMARY AND CONCLUSIONS

A review of the research program is presented through the relevant archival literature. The effect of dissolved gasses and the effect of surfactants are briefly described. The effects of dissolved gasses are investigated experimentally. This effect is small for large temperature drops and for initial value of the solid surface temperature close to the onset of nucleate boiling. These are indeed the conditions closest to a fire application. The effect of surfactants should be explored further in applications where intense cooling is desirable with limited amount of water supply.

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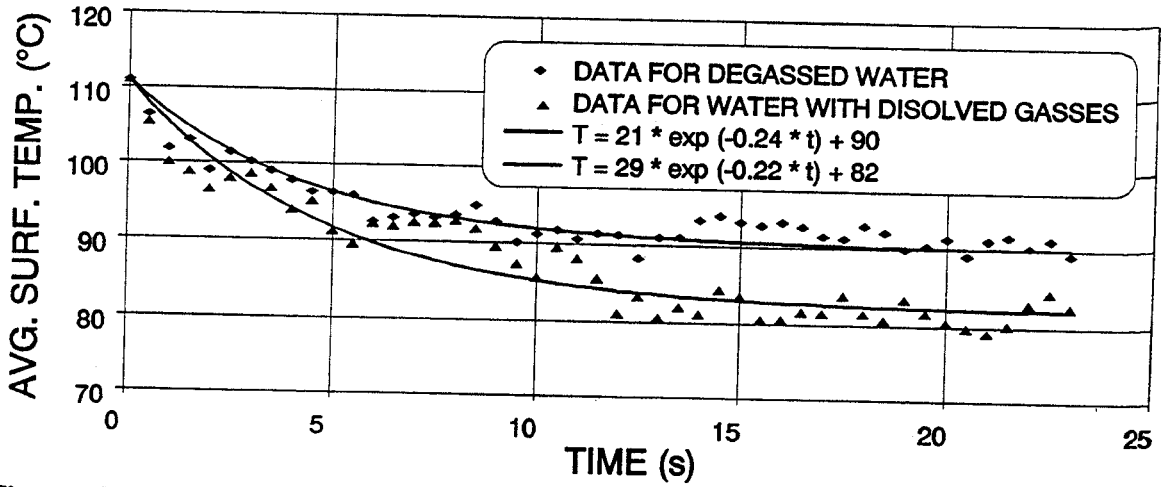

Fig. 1. Transient average surface temperature for T_o = 111 °C and G = 0.21 g/m²s

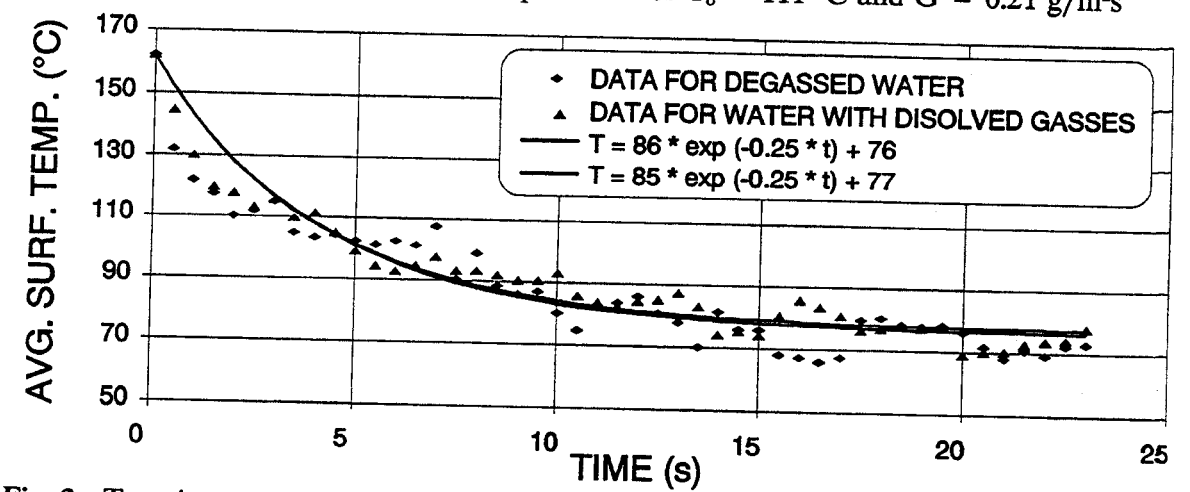

Fig. 2. Transient average surface temperature for T_o = 162 °C and G = 1.5 g/m²s

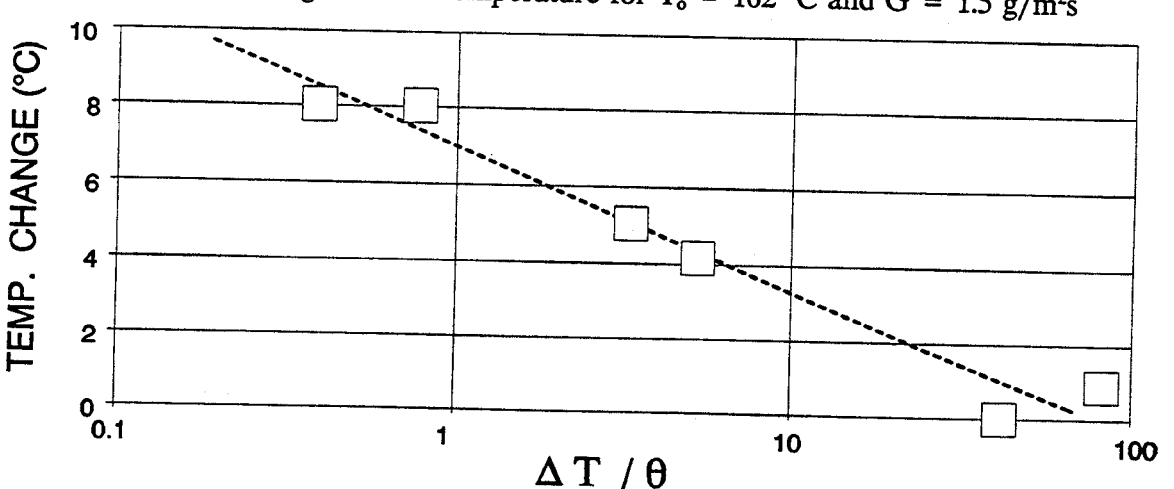

Fig. 3. Effect of dissolved gasses on the variation of the final steady state average solid surface temperature ($T_{degassed}$ - T_{gassed}) as a function of the ratio $\Delta T / \theta$.

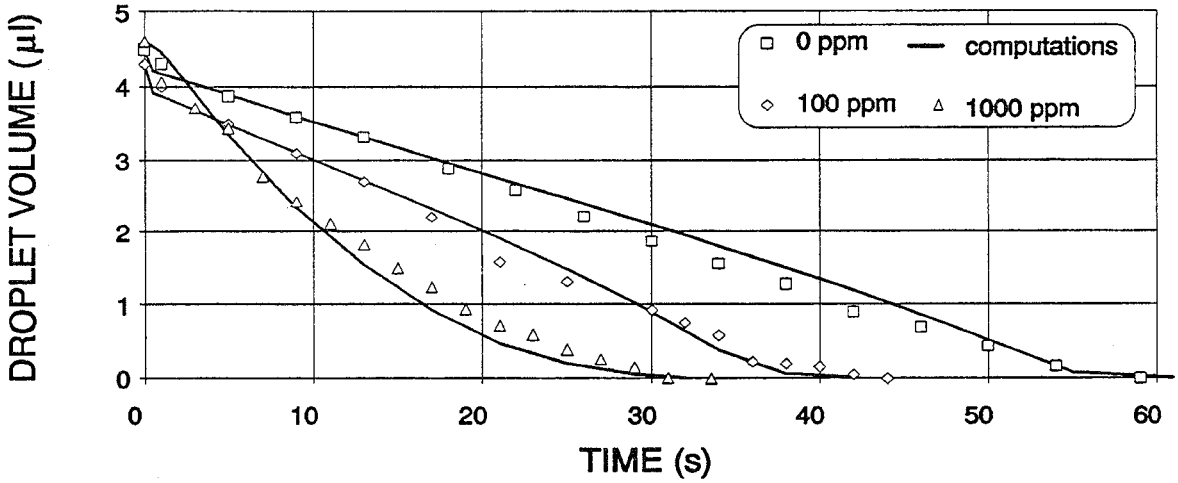

Fig. 4. Droplet volume temporal evolution for T_0 = 80 °C: data and code comparison

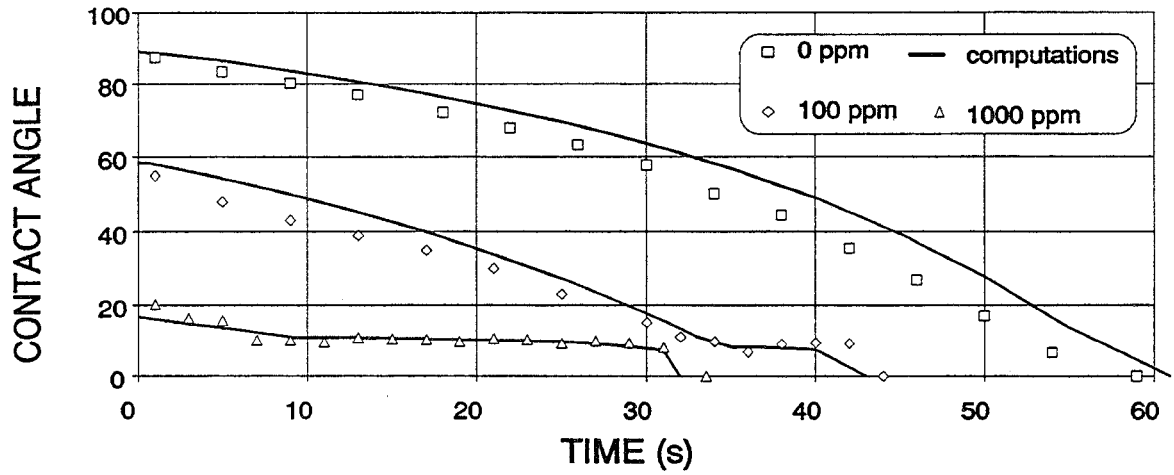

Fig. 5. Contact angle temporal variation for T_0 = 80 °C: data and code comparisons

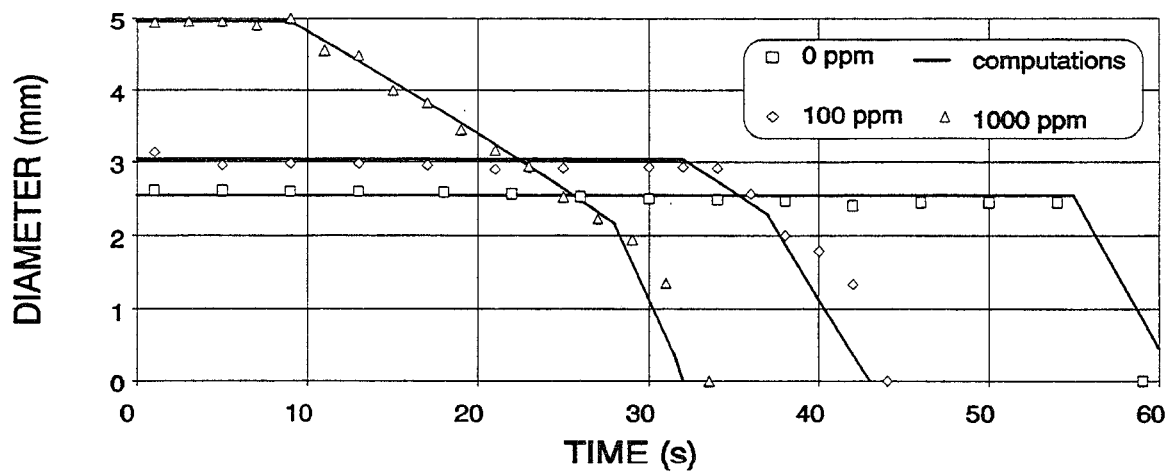

Fig. 6. Droplet diameter temporal variation for T_0 = 80 °C: data and code comparison