

Fig. 1

such enhancement is indeed possible, I would submit that the drop could equally well follow a temperature history like that shown by the dashed line, cooling at a somewhat slower, but still nonzero, rate within the thermal cavity. I would argue further that it is impossible to determine from these data alone what factors in what proportions are responsible for the observed increase in cooling over the Ranz-Marshall correlation. Moreover, due to very complex nature of the processes involved, theoretical analysis is of little value here. The only way to satisfactorily determine the role of dynamic effects is through a very precise experimental study of the cooling that takes place in the first few centimeters of fall. This is, of course, a very difficult experiment. Finally, I would suggest that a falling distance of 3 m is probably too small to determine whether an increase in internal resistance can significantly reduce cooling during the late stages of the life of the drop.

In summary, I would conclude from these observations that the Ranz-Marshall correlation well represents the trend of the data in the range of 0.2–3 m, and that the data are insufficient to draw hard-and-fast conclusions concerning either the very early or the very late stages of a drop's life.

Authors' Closure

The authors are grateful to Porter and Dunn for their discussions which contribute to the understanding of this problem. In most cooling-tower work the analogy between heat and mass transfer is employed. Porter estimated the error as 7 percent. Yadigaroglu and Pastor⁶ conducted systematic study of the comparison of results based upon the Merkel equation and the exact formulation for a cooling tower heat exchanger problem. As to their finding, the error depends on operation conditions and is about 4–7 percent with the Merkel equation giving larger cooling range. But this error will not affect the evaluation of the correction factor *g*. The *g* factor, which is less than 1 for *x/d* > 100, fits the data adequately. This does not imply that the

transfer coefficient from the drop is less than predicted by Ranz-Marshall correlation. The *g* factor compensates for the overprediction by the complete mixing model while actually internal circulation is developing within the drop at *x/d* > 100.

Porter suggests to relate the mass transfer to the mass change in the drop. It will be a very hard task to measure the change of weight of 3–6-mm dia drops which undergo temperature change no larger than 3°C, even by assuming that all the cooling is due to evaporation.

In response to Dunn, in the present experiment the temperature at the drop generator needle was seen to be within 0.03°C of the thermal cavity temperature. Also the drop temperature measured in a small cup at the mount of the cavity (while it partially blocks the opening of the cavity) is in good agreement with the needle temperature. The water temperature in the calorimeter was maintained at about 0.11°C higher than the drop temperature measured in the dewar to compensate for the evaporative cooling of the water in the dewar. The differential was chosen on the basis of a simple analysis which assumed that the drops entering the calorimeter entrain about six times their own volume of air. Thus the cooling of drops in the cavity and in the dewar was prevented approximately.

The first location for measurement of the drop temperature is 17.7 cm from the needle, which is about 44 dia for 4-mm drops. In this falling range strong oscillations of large drops were observed. The augmentation of heat transfer estimated by using the formulas of Scanlan [24] gave reasonable comparisons as suggested by the proposed correction factor *g* in this falling range. Nevertheless, as suggested in the present paper, further investigation on the augmentation of heat transfer by large oscillations in drop shape is needed.

In the range 60 ≤ *x/d* ≤ 600 the internal circulation of large drops is developing. The proposed correction factor gives 1.5–0.3 times the Ranz-Marshall transfer coefficient in the falling range investigated in our experiment. The procedure chosen to explain this behavior and the empirical fit of experimental data is of course not the only possible one as shown by Dunn. However, it provides a systematic approach for further understanding of the transient internal circulation upon drop heat transfer.

Nucleation Site Activation in Saturated Boiling¹

J. J. Lorenz,² B. B. Mikic,³ and W. M. Rohsenow.³ In nucleation experiments with individual cavities, the authors found that the photographically measured cavity radii were equal to those determined from the following well-known nucleation criteria:

$$\rho = \frac{2\sigma T_s V_{fg}}{h_{fg} \Delta T} \tag{1}$$

where ρ is the effective radius of nucleation. Experiments were performed with water only. The authors then suggested that a unique description of the cumulative nucleation site distribution for a given surface could be given by *N/A* versus equation (1).

In an earlier study of the effects of surface conditions on boiling characteristics, we performed nucleation experiments with both water and organics [4, 5, 6].⁴ In our nucleation experiments with water, we obtained results similar to those of the authors', i.e., that the photo-

¹By M. Shoukri and R. L. Judd, published in the Feb. 1975 issue of the JOURNAL OF HEAT TRANSFER, TRANS. ASME, Series C, Vol. 97, pp. 93–98.

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³Massachusetts Institute of Technology, Cambridge, Mass.

⁴Numbers in brackets designate Additional References at end of discussion.

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graphically measured cavity radii were equal to those calculated from equation (1). However, our nucleation results with organics were quite different than those with water. It was found that for the same set of cavities employed in the water nucleation experiments, the effective radii of nucleation as calculated from equation (1) were considerably less than previously calculated for water. Thus, for a given cavity the value of ρ as determined from equation (1) is not unique but depends upon the particular fluid.⁵ Using a model incorporating Bankoff's vapor trapping hypothesis, this difference in nucleation behavior was attributed to fluid-surface contact angle differences between water and organics. For certain cavities dynamic effects also play an important role. Only for very deep cylindrical cavities, which are generally not produced on real surfaces by common finishing procedures, are the influence of contact angle and dynamic effects insignificant, and hence the effective radii the same for water and organics.

Our data for the cumulative nucleation site density on a given surface were consistent with our studies of individual cavities. Fig. 1 clearly shows that equation (1) does not correlate the data for water and organics. By extending our model for individual nucleation sites, this behavior was also explained in references [4, 5] as a contact angle effect. All three organics have nearly the same fluid-surface contact angles and consequently fall on a single curve. Water has a relatively large contact angle and at a given ρ value more sites are active.

Thus, the author's conclusions concerning the nucleation behavior of a particular surface must be restricted to water only. No generalizations can be made to arbitrary fluids.

Additional References

- 4 Lorenz, J. J., "The Effects of Surface Conditions on Boiling Characteristics," PhD thesis, Department of Mechanical Engineering, MIT, Dec. 1971.
- 5 Lorenz, J. J., Mikic, B. B., and Rohsenow, W. M., "The Effect of Surface Conditions on Boiling Characteristics," *Heat Transfer 1974*, Vol. IV, *Proceedings of the 5th International Heat Transfer Conference*, Tokyo, Japan.
- 6 Lorenz, J. J., Mikic, B. B., and Rohsenow, W. M., "A Gas Diffusion Technique for Determining Pool Boiling Nucleation Sites," *JOURNAL OF HEAT TRANSFER*, TRANS. ASME, Series C, Vol. 97, No. 2, May 1975, pp. 317-319.
- 7 Griffith, P., and Wallis, J. D., "The Role of Surface Conditions in Nucleate Boiling," *Chem. Eng. Progress Symp. Series*, Vol. 56, No. 30, pp. 49-63.

⁵ This directly contradicts the results of Griffith and Wallis [7] who claimed that a single dimension is sufficient to characterize a cavity. Employing equation (1) their data for water and organics fell on a single curve. In reference [4] it was shown that the data of Griffith and Wallis is suspect because in performing the experiments, a subcooled bulk temperature was maintained in order to facilitate bubble counting. As a result of the subcooling, air was able to diffuse into the system at the upper surface. It is expected that the presence of this dissolved gas altered the nucleation process in such a way as to fortuitously indicate a unique effective radius of nucleation. In our nucleation experiments a saturated bulk temperature was maintained in order to eliminate this problem.

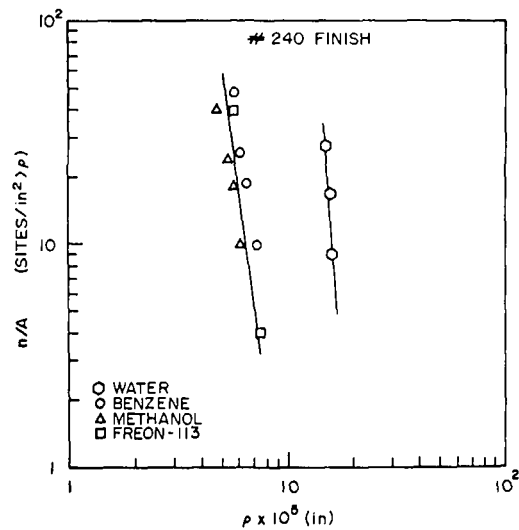


Fig. 1 Cumulative nucleation site densities, reference [5]

Authors' Closure

The authors wish to express their thanks to Lorenz, Mikic, and Rohsenow for their relevant comments. The authors agree that the parameter group $[2\sigma T_s \nu_{fg} / h_{fg} \Delta T]$ represents the effective radius of nucleation ρ rather than the cavity mouth radius r_c . The agreement obtained between the cavity radius and those predicted by the parameter group in the case of water is due to the large contact angle of water which caused the ratio (ρ/r_c) to approach unity.

This fact has been recognized and accounted for in a recently published paper by the authors,⁶ in which (ρ/r_c) was assumed to be function of both the contact angle θ and the cavity conical angle ψ , i.e., $(\rho/r_c) = f(\theta, \psi)$. In this paper the data for boiling of five different organic fluids on a glass surface were used to assess the Mikic and Rohsenow model.⁷ Only the slope of boiling characteristic curve as predicted by the model was found to agree with the experimental data. However, upon introducing the function $(\rho/r_c) = f(\theta, \psi)$, good agreement was obtained when this function was set equal to 0.83 to account for the small contact angle of the organic fluids.

⁶ Judd, R. L., and Shoukri, M., "Nucleate Boiling on an Oxide Coated Glass Surface," *JOURNAL OF HEAT TRANSFER*, TRANS. ASME, Series C, Vol. 97, Aug. 1975, p. 494.

⁷ Mikic, B. B., and Rohsenow, W. H., "A Correlation of Pool Boiling Data Including the Effect of Heating Surface Characteristics," *JOURNAL OF HEAT TRANSFER*, TRANS. ASME, Series C, Vol. 91, May 1969, p. 245.