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DISCUSSION

P. Cohen[4] and G. R. Taylor[5]

The authors comment in their conclusions on the effect of pH and suspended solids on the mechanism of the transfer of heat from surfaces to subcooled water. They observed that in pool nucleate boiling the Δt required for a given heat flux increased as the suspended solids decreased. (Fig. 5 of paper.) They suggest two possible mechanisms for this effect:

1 Nucleation takes place in the superheated boundary layer with suspended solids acting as nucleation sites.

2 The suspended solids in some manner trigger inactive

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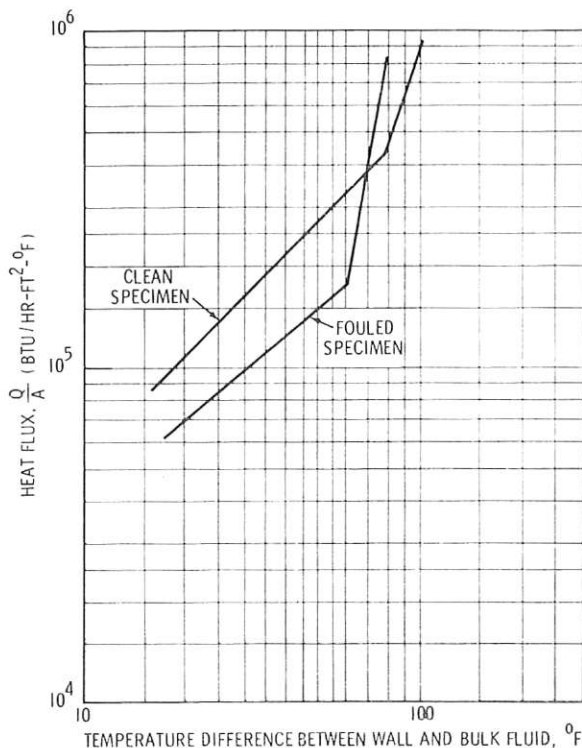

Fig. 13 Temperatures on clean and fouled specimens

nucleation sites on the heated surface into active sites at a lower $(T_0 - T_{sat})$ than would be required in a clean system.

Because of possible implications in water reactor technology the discussers had previously studied the effect of porous deposits of magnetite (similar to those found on reactor fuel) on forced convection subcooled nucleate boiling heat transfer. The results obtained, as outlined below, indicate that such deposits are effective nucleators and *reduce* $(T_0 - T_{sat})$ nucleate boiling for a given heat flux, compared to a clean metallic surface (304SS). Fig. 13 of this discussion presents a typical test result. The electrically heated test section was a hollow cylinder, with an internal thermocouple. T_0 is the calculated temperature of the metallic surface of the specimen. In the forced convection heat transfer regime the specimen metal surface is hotter for the specimen with deposit than for the clean specimen. The value of h for the deposit was separately measured by means of Wilson plots and was of the order of 6×10^3 Btu/hr — ft² — deg F. With a deposit thickness of the order of 1 mil, this corresponds to a value of k for the deposit of 0.5 Btu/hr — ft² — deg F/ft.

At the conditions of the test, $T_{sat} \sim 250$ deg F, the maximum difference between the fouled and clean surface temperatures is some 28 deg F. The fouled specimen entered into nucleate boiling at a metal surface temperature some 20 deg F lower and at a heat flux about one-half of that of the corresponding situation for the clean surface. At higher heat fluxes, in excess of 390,000 Btu/hr — ft², the metal of the fouled surface is actually cooler than that of the clean surface.

Pictures of the boiling process were not taken. Visual observations indicated that the fouled surface had a larger number of nucleations sites, releasing very small bubbles. The clean surface, on the other hand, nucleated at a relatively small number of sites, producing considerably larger bubbles.

It is submitted that these results are consistent with the authors' observations. A thin, porous deposit, formed from precipitated (or settled) particles, impeded conduction, but promoted nucleation and nucleate boiling. The authors' comments on the chemistry of the water are consistent with the probability of obtaining such deposits in the test systems. Separate tests indicated that with our deposits, a change of the pH of the coolant from 7.0 to ~10.0 had no significant effect on the heat transfer process, in either the conduction-convection or boiling regimes, on preformed deposits.

In conclusion, the phenomena noted by the authors is, in our opinion, a result of and an attribute of deposits on the heat transfer surfaces. At higher levels of heat flux corresponding to nucleate boiling on clean surfaces, thin porous deposits can increase the heat transfer coefficient compared to clean surfaces.

Authors' Closure

The comments of Drs. Cohen and Taylor are appreciated. It is gratifying to find that agreement exists with regard to some water chemistry effects for such a large difference in test conditions. However, the specific question concerning suspended solid material in the test fluid or a porous deposit on the test surface for the data of this investigation must be analyzed carefully. It is, of course, possible to have consistency in results but not in the causitive mechanisms. Incidentally, our data are all for saturated conditions not for subcooled conditions as the discussers state.

The discussers' data and their comments about them are as expected for the conditions described. We assume the pressure and bulk temperatures are the same for the two sets of data given. In the nonboiling region, a 1-mil-thick deposit would produce a significant $\Delta T_{Deposit}$ at the high heat flux range shown in Fig. 13. This would cause a higher metal surface temperature than would result for a clean surface. The lower ΔT at incipient nucleation and with nucleate boiling at higher heat flux values which occurred with a deposit on the test surface are probably caused by:

(*a*) The oxide surface having a higher floatability (or is more non-wetting) than a clean stainless steel surface and thus, according to Larsen,[6] nucleation would be expected to begin at lower values of ΔT than for a stainless steel surface, and (*b*) since the oxide surface had considerably different nucleation characteristics (smaller bubble size and larger number of sites) as compared to the stainless steel surface, a lower ΔT at any particular heat flux throughout the nucleate boiling region would result from greater agitation at the surface. In other words, the discussers altered their surface by fouling, changing its nucleation characteristics and its heat flux characteristics in a manner consistent with our present understanding of boiling phenomena.

The discussers' results are different from those shown in Fig. 3 for a clean versus a contaminated surface at low heat flux. We believe that the floatability and change of surface nucleation characteristics had little effect on the results shown in Fig. 3. The insulation provided by the deposit on the surface caused an increase in the ΔT required at a given heat flux. This produced the change in slope shown in the nucleate boiling region.

Figs 4–12 present data for a clean test surface. All data, except those given in Figs. 3 and 4, were taken without removing the particular test section until all tests were completed for that test section. The reproducibility of the data attests to the cleanliness of the test section and the system in general, something confirmed by visual inspection both during and after the tests.

The conclusions reached regarding the effect of suspended solid material in the test fluid on nucleate boiling are based on:

(*a*)　The curves in Fig. 4 which show a progressive shift to higher values of ΔT at a given heat flux with successive tests in the series. (The operating procedure employed and the control of dissolved oxygen were such that a *decrease* in quantity of suspended solids level would be expected.)

(*b*)　Since the data are for a clean test surface, the increase in ΔT between successive runs shown must result from an influence of the bubble nucleation and generation rate on the surface. Photographs taken during runs HI 1–17 and HI 1–21 do not indicate a discernable change in bubble size or site density. Hence it is suggested that the suspended solids influence the bubble generation process such as to require a lower ΔT at a given heat flux than would be required if the particles were absent. Because of these observations, we proposed the bulk phase nucleation hypothesis. Incidentally, it probably should be mentioned that, during one run, photographic data showed a milky cloud type of phenomena around the test section. Exactly what this was made of has never been explained although it had all the appearances of a cloud of millions of minute bubbles. Such a condition could occur if suspended solid particles triggered bulk phase nucleation. This is reported in more detail with the mentioned photograph in reference [1].

(*c*)　Data shown in Fig. 5 are in quantitative agreement with the conclusion that an increase in the level of suspended solids in the test fluid results in a decrease in the temperature difference required at a given heat flux.

As indicated in the body of the paper, additional study is needed to clarify the role of the suspended solid in the nucleation process. The data in Fig. 13 should be viewed as discussed previously in relation to Fig. 3. We feel that a conclusion relative to the influence of suspended solids *in the fluid* on nucleate boiling cannot be reached from these two figures.

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[6] R. F. Larsen "Factors Affecting Boiling in a Liquid," *Industrial and Engineering Chemistry*, vol. 37, 1945.