

Effects of Oily Fluid and Surface Contaminants on Heat Transfer to Boiling Water

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INTRODUCTION

The quantitative prediction of nucleate boiling heat transfer for various fluid metal surface combinations is very difficult. Fouling of the heat transfer surface due to deposits, corrosion, etc., presents an even more difficult task to the designer trying to predict boiling heat transfer coefficients. In particular, fouling due to high molecular weight petroleum-based preservatives and lubricating oils used in steam plant components is of interest. This paper provides some heat transfer data on artificially fouled, electrically heated tubes with various combinations of sludge and oily contaminant mixtures.

The initial studies of Jakob and Fritz (1931) consisted of some qualitative investigations of boiling from roughened surface coated with oil. It was noted that the bubble contact angle was above 90° (nonwetting) prior to bubble departure and the bubble departure diameter was larger than for a clean surface. The oil was washed off after a short time, and no steady state thermal data could be recorded.

Heat transfer literature indicates that boiling heat transfer is impaired by an early transition from nucleate boiling heat transfer to a film boiling condition if the surface wettability is reduced, e.g., if oils, etc., are introduced which result in poor wetting of the material surface. Large bubbles then become predominant. However, in the case of nonwetting spots (Teflon) on an otherwise wetted metal plate considered by Young and Hummel (1964), a significant improvement in heat transfer was obtained over that for a clean flat metal plate. Hermann and Hsu (1972) showed that coating the tubes with a fluorinated methacrylate material with a lower wettability than Teflon (also a lower surface energy) also improved the heat transfer characteristics. As previously noted for the oils, the coating was removed by the boiling action at high heat fluxes. Jensen et al. (1979) provided a summary of additional work done on the degradation of heat transfer from tube surfaces with various oil films and provided data for cosmoline, turbine oil and fuel oils using distilled water and phosphate water additive. The data presented in this paper will be compared to some of the data of Jensen et al. to highlight the differences between the two data. The present study was done to obtain additional test data on the effects of various oily surface and fluid contaminants on heat transfer characteristics.

TEST APPARATUS

The test apparatus consisted of a variable direct current power supply which was used to electrically heat the 1.43 cm outside diameter (0.17 cm wall thickness) by 20.32 cm long Inconel (of the International Nickel Co.) Alloy 600 tubes. The tubes were vertically oriented and placed in an open beaker (atmospheric boiling) which had an auxiliary heater to maintain the fluid in the beaker at the saturation temperature. Two different water additive solutions were utilized in the beaker fluid. The first water solution used a 2.25 ppm concentration of morpholine, while the second used a concentration of 225 ppm of disodium phosphate. A drip feeder was utilized to maintain constant water levels. The tubes had two

chromel-alumel thermocouples welded to the tube inside diameter at 5.08 cm and 12.7 cm from the bottom of the tube. The wall superheats are averages of these thermocouples corrected to the outside wall temperature by the temperature drop through the tube wall. The tube was clamped at the top and bottom such that the tube could be easily changed, and the clamps also provided the electrical path for obtaining the desired tube heating. The tube wall thermocouples, tube voltage and current (power input), and bulk fluid thermocouples were scanned and averaged over a 1-s period and were recorded. The different test configurations are provided below.

TEST CONDITIONS

The various tube configurations tested under atmospheric boiling conditions in the different water chemistries noted above were:

1. Plain tube.
2. Tubes coated with an iron based sludge mixture (80 w/o) and 20 w/o Grade 1 (1058) cosmoline (petroleum ether was used as the cutting agent for the cosmoline), baked in a vacuum oven ($T = 82.2^\circ\text{C}$) for 3 hours and vacuum dried for 36 hours at ambient temperatures.
3. Tubes coated with Grade 1 cosmoline (1058) only (petroleum ether was used as the cutting agent).
4. Tubes coated with turbine oil only.
5. Plain tubes where cosmoline is added to the beaker solution.
6. Plain tubes where turbine oil is added to the beaker solution.

The thicknesses of the tube deposits were not specifically measured but are estimated to be on the order of 0.013 cm and were fairly uniform around the circumference and axially.

TEST RESULTS

Figure 1 provides the test data for a plain tube in the two different water solutions. For comparison, the vertical tube data of Jensen et al. in distilled water are provided. A single data point using distilled water and a plain tube at the lowest heat flux ($54,000 \text{ W/m}^2$) indicated similar performance as for the plain tube with a morpholine solution. It should be noted that the data of Jensen et al. (1979) indicated that tube orientation (vertical or horizontal) did not make a significant difference in the overall heat transfer characteristics. Our data are in relative agreement with those of Jensen et al., but these data have a different slope. This may be due to different tube surface conditions. The data indicate slightly better heat transfer characteristics (lower wall superheat hence higher heat transfer coefficients at a given heat flux) in the morpholine solution than in the phosphate solution. No dryout data were obtained since the boiling action was too violent to go above a heat flux of approximately $150,000 \text{ W/m}^2$. When a mixture of sludge and cosmoline was put on the tubes, the data indicated only a slight degradation in heat transfer characteristics at the higher heat fluxes. In this case, the phosphate solution provided slightly better heat transfer characteristics than the morpholine solution. It should be noted that the sludge layer tended to flake off from various sections with time as has been noted for oil deposits by Jakob

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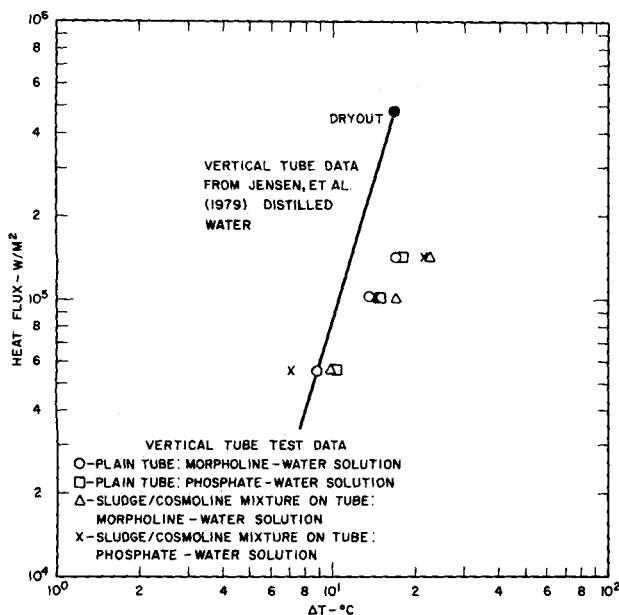


Figure 1. Effect of sludge/cosmoline on heat transfer.

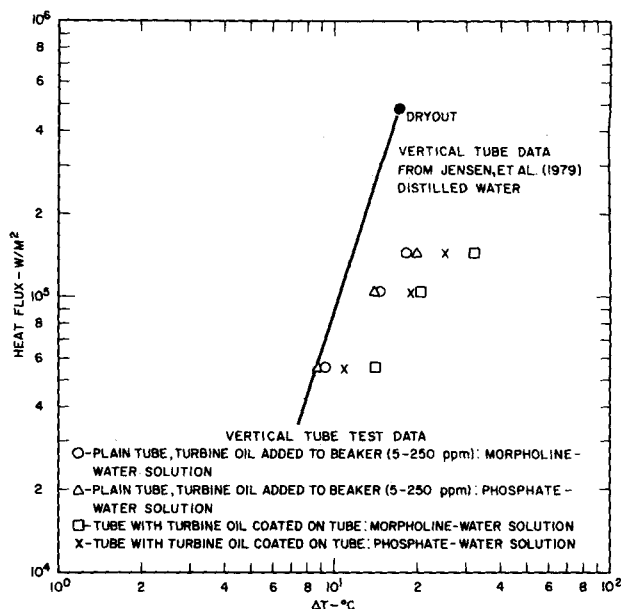


Figure 3. Effect on turbine oil on heat transfer.

et al. It is judged that the iron-based sludge reduces the influence of the cosmoline coating in reducing the heat transfer as is noted in Figure 2 for cosmoline only.

Figure 2 indicates the effect of cosmoline only when it was either painted on the tubes (both water solutions) or added to the surface of the beaker (morpholine solution only). For these conditions, considerably worse heat transfer characteristics (higher wall superheats) are obtained and dryout was obtained at a heat flux of approximately 146,000 W/m². There was only a slight advantage noted for the morpholine solution for the case of painting the cosmoline on the tubes. There was only a small degradation (at the high heat fluxes) noted when the cosmoline was added to the beaker. A slight improvement was noted at the lower heat flux. This may be related to the time necessary to get the cosmoline in the solution to deposit on the tube surface and inhibit the heat transfer.

It should be noted that these results are completely reversed from the results reported by Jensen et al. (1979), Figure 2. Their results showed an improvement in heat transfer as the cosmoline con-

centration was increased. This difference may be due to the cutting agent used to fluidize the cosmoline. We used a very volatile petroleum ether, while Jensen et al. used benzene. Benzene tends to form an azeotropic solution (constant boiling point) and may have biased the test results. Our data supports the theory that cosmoline (a petroleum-based preservative) degrades boiling heat transfer. The magnitude of the dryout heat flux (146,000 W/m²) is somewhat lower than the value obtained by Jensen et al. (250,000 W/m²).

Figure 3 shows the influence of turbine oil on heat transfer performance. In the case of adding turbine oil to the beaker (5 to 250 ppm concentrations), there was little effect compared to the plain tube data (Figure 1), no variation with these concentration levels, and very little effect of water solution. However, when the tube surfaces were coated with turbine oil, there was a considerable degradation of heat transfer characteristics. In this case, the phosphate solution, as might be expected since the phosphate will act as a detergent to remove the oil, had less degradation than with the morpholine solution. As previously noted, the oil film did tend to be removed by the boiling action, particularly at the higher heat fluxes although no heat transfer performance increases were noted as a result of the oil film removal.

CONCLUSIONS

The testing described above leads to the following conclusions:

1. The influence of using either a phosphate or a morpholine water solution is significant only for the turbine oil case for the surface conditions tested since the phosphate solution can act as a detergent and remove the oil in that case.
2. The use of cosmoline will definitely provide a decrease in the boiling heat transfer coefficient as well as a lower dryout heat flux compared to a plain tube dryout heat flux.
3. Coating the surface of the tubes with an oil contaminant provides a significantly larger decrease in the boiling heat transfer coefficients compared to adding similar contaminants to the boiling solution for these short-term tests. Longer-term tests would be needed to show how the oily contaminant would deposit on the tube surfaces and over the long term influence the overall heat transfer coefficients.
4. For tubes coated with a sludge/cosmoline mixture, there is a decrease in the boiling heat transfer coefficients at the higher heat

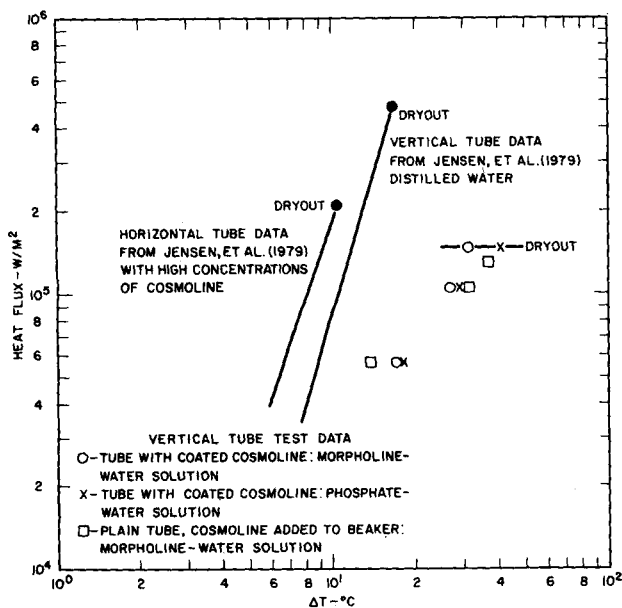


Figure 2. Effect of cosmoline on heat transfer.

fluxes, but the decrease is less than that obtained from coating the tube surface with cosmoline only.

5. The results of this testing indicate that extraordinary care should be exercised in plant operations to prevent the introduction of petroleum-based compounds into the heat exchangers which can result in the fouling of the heat transfer surfaces.

ACKNOWLEDGMENT

This paper was prepared as an account of work sponsored by the U.S. Government. Neither the U.S. or the U.S. Department of Energy, nor any of their employees, contractors or subcontractors, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

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Manuscript received May 11, 1983; revision received July 25, and accepted August 21, 1983.

Interfacial Distribution Between a Membrane and the Adjoining Free Solution

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This paper deals with the interfacial equilibrium between the membrane surface and the adjacent homogeneous liquid/gaseous solution.

In membrane separation processes, such as reverse osmosis, ultrafiltration and pervaporation, there is a liquid/gaseous solution under high pressure on one side of the membrane and liquid or gas at low pressure on the downstream side. All permeate molecules move under the combined influence of concentration and pressure gradients. The description of this process requires the flux equations in the membrane phase and the interfacial distribution relations between the membrane phase and the adjacent solution phase (interfacial equilibrium).

The flux equations have been derived based upon irreversible thermodynamics, where the flux is described as the linear combination of independent driving forces such as chemical potentials (Kedem and Katchalsky, 1958; Spiegler and Kedem, 1966). Lightfoot (1968, 1974) derived the flux equations under the framework of the Stefan-Maxwell equations, which relate the driving force as the linear combination of the fluxes. The Kedem Katchalsky equations (1958) were also justified by Lightfoot (1974) based upon the Stefan-Maxwell equation with the Kirkwood formulation. The diffusion theory, which is the most simplified version of the flux equations mentioned above, has been developed and widely used especially in describing solvent permeation through a polymeric membrane (Merten, 1966; Paul and Ebra-Lima, 1970).

To integrate the flux equations, appropriate boundary conditions should be specified at the points within membrane on the upstream and on the downstream side. The boundary conditions are the pressure and the pressure-independent activities of the permeate species at both membrane surfaces. It is very difficult to measure and then specify the boundary values. However, the boundary values can be related to the measured pressures and concentrations of the solutions adjacent to the membrane surfaces, by assuming interfacial equilibrium. At both membrane surfaces, the abrupt

changes in concentration and pressure occur across the boundary between a membrane and the adjoining solution. Concentration and pressure gradients in the two solution phases are negligible compared to the interfacial gradients across the boundary. Therefore, the resistance to flux across the boundary is negligibly small, so that equilibrium should exist between the species i just inside the membrane and i in the adjacent solution (Rosenbaum, 1968; Lightfoot, 1974). It should be noted that interfacial equilibrium does not necessarily imply the continuity of pressure across the boundary (Gregor, 1948, 1951; Lightfoot, 1974). However, Paul and Ebra-Lima (1970) suggested the approximation that the pressure within the membrane is constant and equal to that in the solution on the upstream side. This approximation was used in modelling the pervaporation processes (Greenlaw et al., 1977a,b). Rosenbaum (1968) suggested that in a nonporous membrane the pressure within the membrane is independent of location and is of a constant value, P_m . Several authors have derived interfacial equilibrium equations under the various constraints imposed upon the standard chemical potentials and the reference pressures.

The purpose of this paper is to present a generalized interfacial equilibrium equation which can be simplified for special cases to give previously reported equations, Table 1. It is also shown that the proper choice of the standard chemical potentials and the reference pressures gives an interfacial equilibrium equation which can be conveniently used to calculate the distribution (partition) coefficient between the membrane-solution boundary. The equations derived in this paper can be applied to ultrafiltration, reverse osmosis and gas separation by a polymeric membrane.

GENERALIZED INTERFACIAL EQUILIBRIUM EQUATIONS

When the concentration and pressure gradients in the solution are negligible compared to the interfacial gradients across the