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SUBJECT: PRELIMINARY RESULTS ON FLINAK HEAT TRANSFER

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PRELIMINARY RESULTS ON FLINAK HEAT TRANSFER

Summary

Heat transfer coefficients have been measured for flinak flowing turbulently in both nickel and inconel tubes. The data obtained using the nickel tube lie in the hydrodynamic transition region and substantially check the heat transfer correlation for most ordinary fluids. The inconel tube data fall considerably below the expected correlation. It is believed that this discrepancy is due to a film formed on the surface of inconel in the presence of flinak. The existence of this film has been demonstrated and its composition partially determined.

Apparatus

Tests on convective heat transfer with flinak were performed in a manner similar to that used in the study of molten sodium hydroxide heat transfer.[1]

The apparatus used for the sodium hydroxide study was modified to incorporate metals compatible with flinak and to provide a more flexible experimental system. Nickel will contain flinak but is subject to fatigue failure at temperatures above 1000°F. Therefore, inconel, which retains its structural strength to very high temperatures, was used as the material of construction.

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1. Hoffman, H. W. - "Turbulent Forced Convection Heat Transfer in Circular Tubes Containing Molten Sodium Hydroxide," ORNL-Physics Report 1370.

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One of the major inconveniences encountered with the sodium hydroxide experimental system was the inability to easily replace system components. The changes made to remedy this situation will be described in detail in a final report on flinak heat transfer. In essence these involved the use of flanges and O-ring seals on the tanks and Swage-lok unions to connect the test section to the system. The latter modification was made to facilitate interchange of test units. Minor changes were also made in the mixing pots.

The scale used in the weight-rate determination was oriented such that the wheels were "in-line" with the direction of thermal expansion of the system. A turn-buckle arrangement was connected to the scale such that the weigh tank could be moved to compensate for the thermal expansion of the connecting lines and the test section. In this way buckling of the test section was prevented. In addition, the power terminals were supported on roller bearings so as to further eliminate strain in the test section. The net result was a test section which was undistorted at the conclusion of the series of runs.

The flinak was pushed through the test section from one tank to the other by means of the pressure of the inert gas blanket, as was done in the sodium hydroxide experiment.

Results

A series of runs was made using a nickel test section, 3/16" O.D. x 0.035" wall thickness. The data obtained are shown in Figure 1. The results cover the transition flow region and check generally the correlation for ordinary

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fluids ($0.5 < Pr < 100$). An attempt to obtain data in the region of fully developed turbulent flow by raising the temperature was unsuccessful due to failure in fatigue of the nickel tube. The data demonstrate that variations in the entrance conditions, arising from slight differences in geometry between the two ends of the test section, strongly affect transition region heat transfer. Thus, the results for flow through the test section in one direction are indicated by the normal triangles in Figure 1, while the inverted triangles are for flow in the opposite direction.

The nickel tube was then replaced by an inconel section, 0.225" O.D. x 0.025" wall thickness, and a second series of runs performed. The result of this test series is shown in Figure 1 by the open circles. The data extend through the transition region into the regime of fully developed turbulent flow. It is apparent that the flinak heat transfer is considerably lower (by a factor of two) than the heat transfer for sodium hydroxide or air. Since the Prandtl modulus for flinak lies in the same range as that for sodium hydroxide, the flinak-inconel data should fall on the curve correlating heat transfer for the ordinary fluids. In addition, these data are inconsistent with those previously obtained for flinak flowing in a nickel tube.

There are three possible explanations of the observed differences:

(1) The experimental measurements are in error

(2) The physical property data used in the analysis are incorrect

(3) "Non-wetting" occurs or an interfacial resistance (film) exists at the metal surface

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The coefficient of heat transfer is defined by the equation,

$$h = \frac{(q_f/A)}{(t_s - t_m)} \tag{1}$$

where (q_f/A) is the thermal flux through the metal-fluid interface, t_s, the temperature of the metal surface at this interface and t_m, the mixed-mean temperature of the fluid. Accounting for the discrepancy on the basis of experimental error requires that either the thermal flux be twice that measured or that the temperature difference be half that observed or that errors in the proper direction exist in both quantities.

Excellent heat balances (95 to 99%) eliminate the possibility of error in the thermal flux. While it was unlikely that a consistent error could occur in all nineteen of the tube surface thermocouples, the calibration of these couples was checked. The test section was cut into small lengths each of which encompassed a tube surface thermocouple. Then each couple was checked at the temperatures corresponding to the melting points of lead, zinc and aluminum. No significant deviation from the expected calibration was observed.

Similarly, the calibration of the thermocouples used in measuring the mixed-mean temperatures was verified. An analysis of the mixing-pots indicated that the mixed-mean fluid temperatues could be in error due to heat conduction losses from the thermocouple junctions. Although the probability was low that these losses were large enough to account for the variation in the data (an error of 10 to 20°F being required), the mixing-pots were redesigned to insure that the thermocouple lead wires remained in a longer constant temperature region.

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A change in the thermal conductivity of flinak from 2.6 to 0.88 Btu/hr-ft-^{o}F or a change in the viscosity from 11 to 0.02 lbs/hr-ft or a combination of these two would be necessary if the data are to fit the accepted correlation. The magnitude of these changes is so large as to virtually preclude this possibility. Moreover new physical property data for flinak (thermal conductivity and viscosity) indicate the values used to be substantially correct.

The existence of a "non-wetting" condition is eliminated by evidence showing that flinak readily wets inconel surfaces. However it is possible that a film caused by a reaction between flinak and inconel forms on the inside tube surface. A section of the tube used in the second series of runs was cut longitudinally and examined for the presence of a film. While there were indications that a film was present its existence could not be conclusively established since the tube contained solid flinak.

A third series of runs was made with an inconel test section and the modified mixing-pots. Only two points were obtained before shut-down resulting from failure of a system component. These are shown in Figure 1 by the closed circles and are sufficient to check the data of the second series. It can be concluded that the difference between the observed and expected heat transfer is definitely not due to errors in the measurement of the mixed-mean temperatures.

The test section from this series was cut longitudinally; and a green deposit, extending over the entire inside surface of the tube, was observed. With the film present, the coefficient of heat transfer is given by the equation,

$$h' = \frac{1}{\frac{(t_s - t_m)}{(q_f/A')} - \frac{x}{k}} \qquad (2)$$

where A' is the inside surface area of the film, x, the film thickness and k, the thermal conductivity of the film. Since the films are thin, probably on the order of 1 mil, the ratio of the heat transfer area of the film to that of the clean tube, A'/A, is approximately one. Hence, (q_f/A') in equation 2 may be replaced by (q_f/A). Equation 2 can then be written, substituting from equation 1,

$$h' = \frac{1}{\frac{1}{h} - \frac{x}{k}} \qquad (3)$$

The inconel tube data, recalculated using equation 3 and assuming the thermal resistance (x/k) to be 0.002 $(\text{Btu/hr-ft}^2\text{-}^\circ\text{F})^{-1}$, appear in Figure 2. From this figure it is seen that the observed film with its postulated properties (e.g., k = 0.5 Btu/hr-ft-°F and x = 1.2 mils) is sufficient to account for the variation in the data. The scatter exhibited by the corrected data probably results from the lack of knowledge as to the exact film thickness for each run.

The film was examined by petrographic and electron diffraction techniques so as to determine its composition. The results of this examination are shown in the following table:

Examining Technique	Sample Source	Composition
Petrographic	Film on tube	Cr_2O_3, Ni_2O_3, NiO
Petrographic	Crystals in mixing-pot	K_3CrF_6, Li_3CrF_6
Electron diffraction	Film on tube	K_3CrO_4, NiO

Thus, while the exact composition of the film is not firmly established, it is apparent that it contains chemical combinations of the elements present in the system (potassium, lithium and fluorine from the flinak, and nickel and chromium from the inconel).

During preparation the flinak was treated such as to eliminate the water present in association with the fluoride salts. The space above the melt was evacuated and then dry, inert gas was bubbled through the salt. This cycle was repeated at a half-hour frequency during the preparation of the flinak. At each start-up of the system following replacement of the test section, the same procedure was used. Pretreatment of the tube surfaces to remove the metal oxides was not attempted. Thus, the oxygen present may occur in the system in the form of residual water in the flinak and/or metal oxides on the inside surface of the tube.

A check was made to determine if the current flowing through the tube wall of the test section influenced the film formation. A piece of inconel tubing was allowed to remain in a still pot of molten flinak for 24 hours. On

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removal a green film was observed on the tube. It is to be noted that a piece of nickel tubing showed no film under similar conditions.

Discussion

From the experiments described in the preceding section, it appears that a film is formed on an inconel surface in the presence of flinak which materially affects flinak heat transfer. Further work is planned to determine the thickness and thermal conductivity of these films. An attempt will again be made to obtain some data for flinak in fully developed turbulent flow within a nickel tube.

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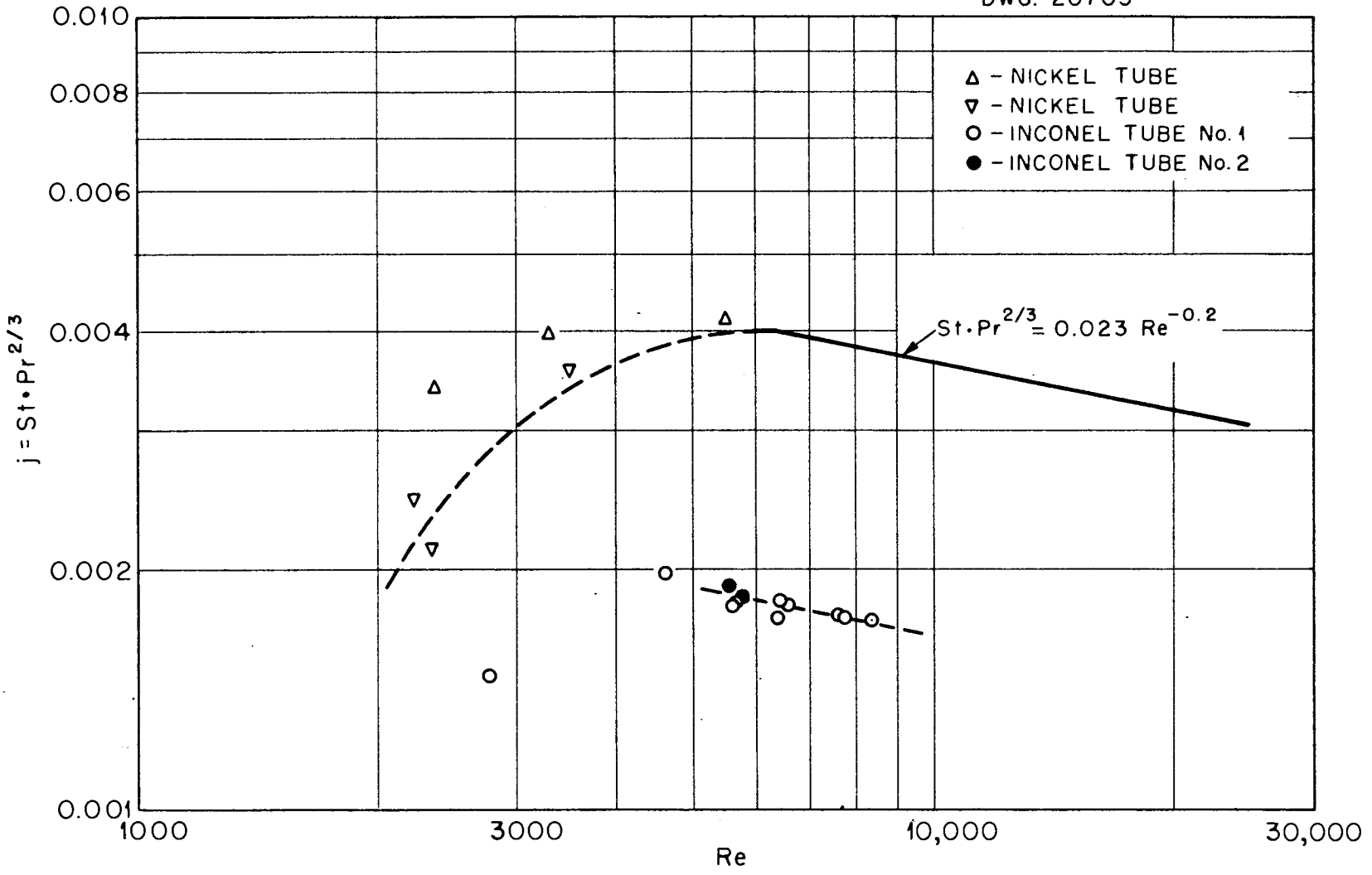

Fig. 1. Flinak Heat Transfer

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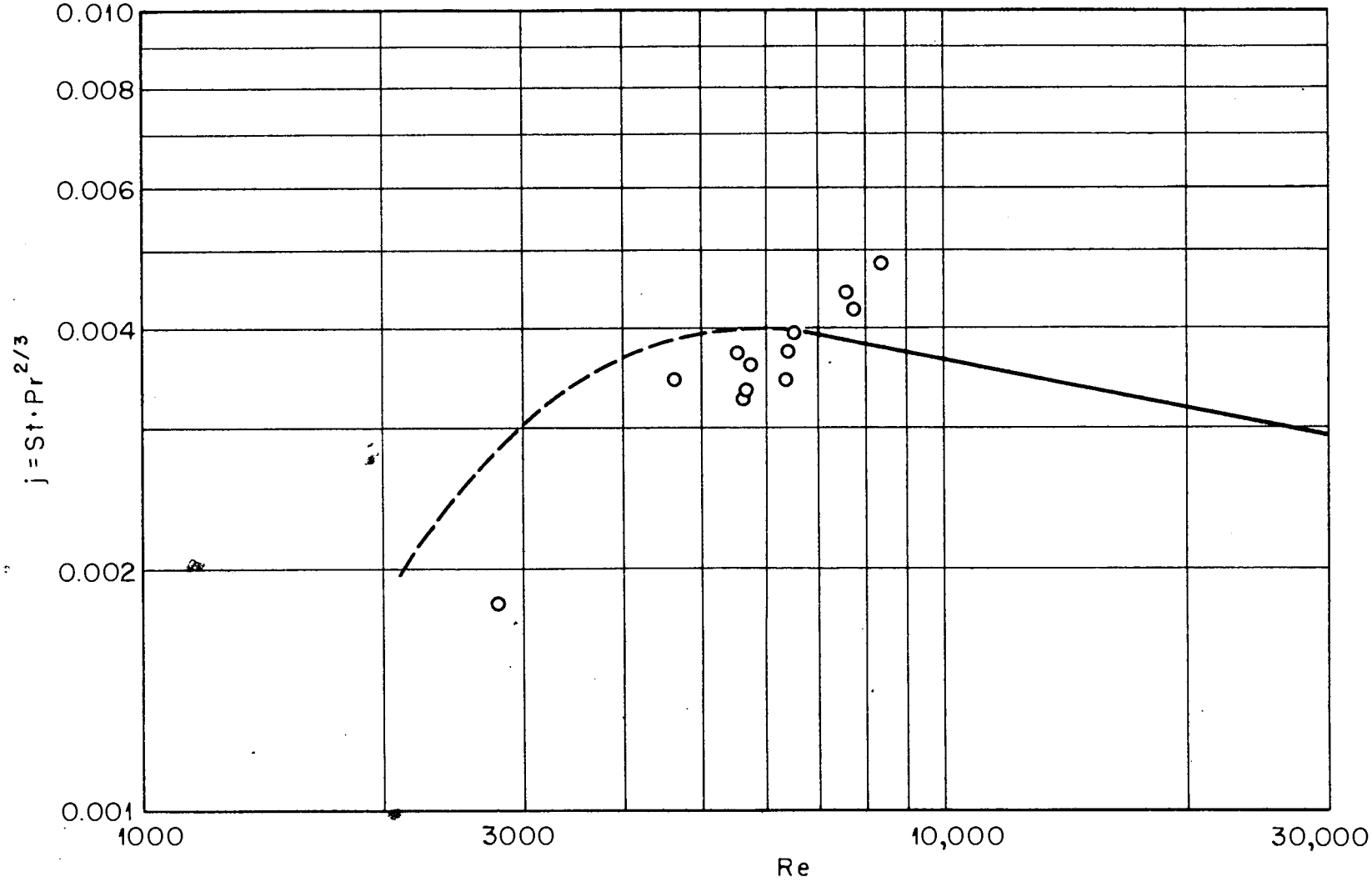

Fig. 2. Adjusted Flinak Heat Transfer