Forced Convection Boiling of Potassium-Mercury Systems

Y. S. TANG, P. T. ROSS, R. C. NICHOLSON, and C. R. SMITH

General Motors Corporation, Indianapolis, Indiana

Many investigations are currently being conducted to obtain forced convection boiling heat transfer information for liquid metal systems; however only limited results have been published, and no information is available regarding a binary metallic system.

This study was initiated to obtain the boiling heat transfer characteristics of different compositions of potassium amalgams. The information is required for the proper design of a thermal regenerator in a liquid metal electrochemical cell system (*1*). Initial results of the first series of experiments with a 44.5% K (by weight) amalgam were previously reported (*2*). This paper presents, in addition to the previously reported data, the results of a second series of experiments with a 44.5% K amalgam and the experiments with a 14.7% amalgam.

Studies made with boiling binary systems of water and organic liquids (*3, 4, 5*) indicate that the critical heat flux for boiling binary mixtures may be higher than that of either component. In addition the boiling heat transfer coefficient of certain compositions reaches a minimum value lower than that of either component. This finding is in accordance with the theoretical prediction of Scriven (*6*) based upon an evaluation of the bubble growth coefficients. It is therefore conceivable that the same phenomenon may exist in a binary liquid metal system, and the boiling characteristics of pure components can not be used as limits for mixtures of these components.

EXPERIMENTAL APPARATUS AND MEASUREMENTS

The experimental liquid metal loop used is shown schematically in Figure 1. The amalgam flows clockwise from the electromagnetic pump through the preheater, then into the test section where boiling occurs. From the boiler the amalgam flows through an enlarged section, where void fraction is measured, into an air-cooled condenser. After being condensed the amalgam flows through the downcomer and is returned to the pump. Mounted in the downcomer is a finned tube heat exchanger which can be supplied with either hot or cold air to obtain the desired preheater inlet temperature.

The test section consists of a ⅜-in. O.D. by 0.035-in.-wall stainless steel tube. The tube was inserted between the halves of eight 0.828-in.-thick copper disks spaced 0.063 in. apart. To ensure a good thermal contact between the tube and copper disks the inside of each disk was silver plated before being mechanically bound with the tube by means of bands outside of the disks. These copper disks were 6.0 in. in diameter and contained as a heat source cartridge heaters with a maximum sheath temperature of 1,600°F. The boiler is capable of supplying 12.6 kw. to the inner diameter of the tube (Figure 2). A similar design was used for the preheater which provided a maximum of 6.3 kw.

Each disk was instrumented for calculating film coefficients. Four ⅛-in. chromel-alumel thermocouple probes were embedded in each copper disk for radial temperature profile measurements. This permitted the heat flux density to be calculated for each disk. In addition similar thermocouple probes were employed to measure the tube wall temperature between the disks of the boiler. By interpolation of the measured tube wall temperature profile the temperature of the tube wall at each plane of radial temperature probes was obtained. A typical temperature profile is shown in Figure 3.

The inner tube wall temperature was evaluated by extrapolation across the stainless tube wall with the previously determined heat flux density. Owing to the heating characteristic of the heaters, the heat flux densities varied with the axial lo-

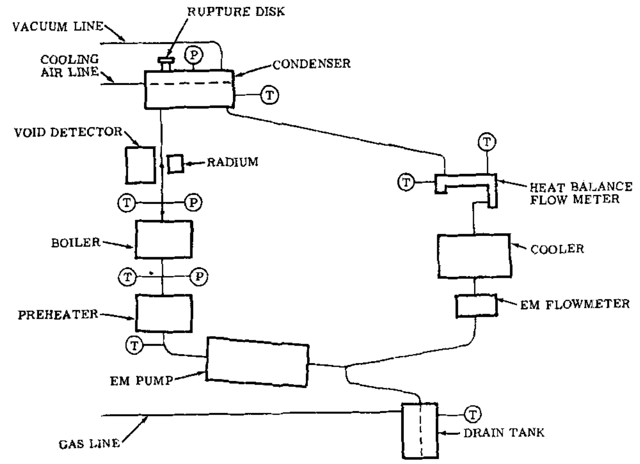

Fig. 1. Schematic diagram for boiling liquid metal heat transfer loop.

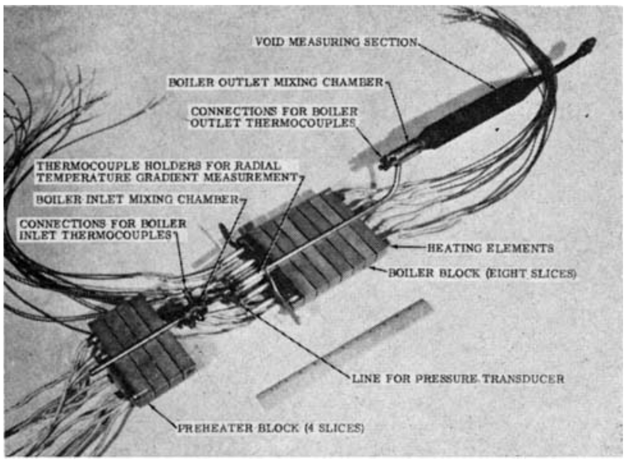

Fig. 2. Cross section of the preheater and boiler test section.

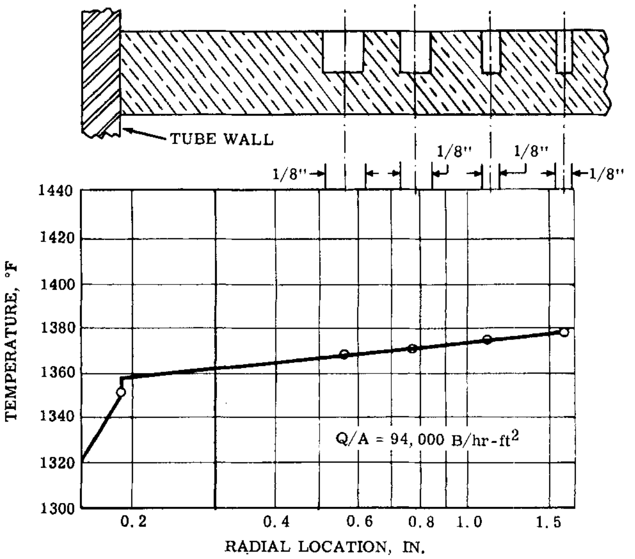

Fig. 3. Radial copper block temperature profile.

cation. To prevent tube wall burnout a rate-of-temperature-change indicator with a circuit disrupter was placed in series with a tube wall temperature probe.

The pressure of the system was measured at both the boiler inlet and boiler outlet. The pressure probes were designed for high-temperature operation and utilized nack (NaK) as a transmitting fluid from the aft side of the diaphragm to a remotely located bourdon gauge. The bourdon gauge signal was converted to a millivolt output.

Flow measurements, necessary for calculation of the quality of the two-phase flow, were obtained by two different devices. The primary instrument for measuring flow rates was a heat-balance flow meter located just downstream of the condenser. It consisted of an electrical heating element immersed in the flow stream and thermocouples located at the inlet and outlet of the meter to measure the temperature rise of the fluid passing through the flowmeter. A secondary flow meter was also incorporated in the system to provide a more rapid response to changes in flow rate. This secondary device was an electro-magnetic flow meter which was calibrated with the heat-balance flow meter.

A void fraction detector with attenuation of gamma radiation was installed immediately above the boiler outlet. The void detector was calibrated with mercury in the tube before installation. The 0 and the 100% points were adjusted at the beginning of each experiment.

For heat transfer evaluations the following measurements were recorded: the temperature of the liquid metal at the boiler inlet and outlet mixing chambers, the four radial temperatures in each copper disk, the tube wall temperature between disks of the boiler, and the pressure at the boiler inlet and outlet mixing chambers.

With flow rates and heat flux densities used, vapor quality was calculated with the heat of vaporization data from the literature (7). Net boiling at the outlet was also indicated by the void fraction detector reading. The presence of net boiling in any disk was determined by the enthalpy change of the fluid, which in turn indicated that the fluid reached the saturation temperature corresponding to the pressure in the boiler. Since at the boiler inlet the fluid was 100° to 300°F. below the saturation temperature, a portion of the boiler was required to provide the sensible heat necessary to reach saturation. The presence of surface boiling was assumed at that disk where the inner tube wall temperature exceeded the saturation temperature. When this occurred in a portion of the disk, the data point at that disk was excluded. The mean fluid temperature at each disk was calculated with a heat balance for the individual disk. The typical temperature profiles of outer and inner tube wall and the liquid metal are shown in Figure 4. The change of saturation temperature with pressure variation was found to be negligible. The temperature difference between the heating surface and bulk fluid was used for the calculation of heat transfer coefficients. The wall superheat ΔT is defined as the difference between T_W and T_{SAT} in both net and surface boiling conditions. For comparing the boiling coefficients h_B with single-phase nonboiling forced convection coefficients h_o nonboiling experiments with both compositions were also made.

RESULTS AND DISCUSSION

Net Boiling Data

Values of heat flux density for the net boiling region of the test section are plotted in Figure 5 as a function of the wall superheat $\Delta T = (T_W - T_{SAT})$. The results of both compositions (44.5 and 14.7% K by weight) are shown in Figure 5. A range of ΔT from 70° to 400°F. was covered for 44.5% K amalgams at pressure levels of 1.5 to 3.5 and 11 to 13 lb./sq. in. abs. A summary of all experimental results is shown in Table 1*. For 14.7% K amal-

* Tabular material has been deposited as document 7975 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or $1.25 for 35-mm. microfilm.

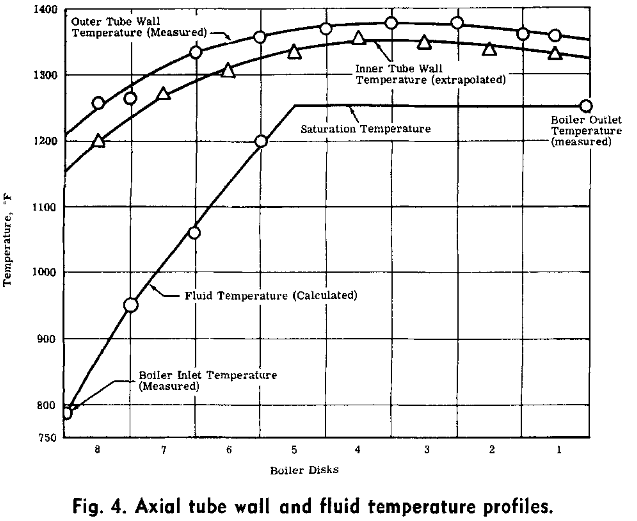

Fig. 4. Axial tube wall and fluid temperature profiles.

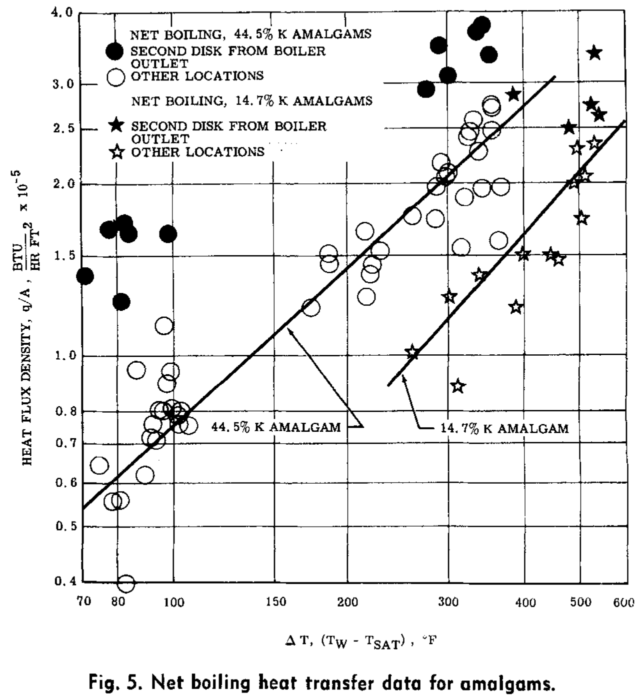

Fig. 5. Net boiling heat transfer data for amalgams.

gams about 70% higher wall superheat ΔT was required for net boiling at a given heat flux density. This phenomenon is similar to that experienced with pure mercury. The lines in Figure 5 represent the recommended correlations of (q/A) vs. ΔT for these two compositions. As shown in Figure 5 data points for each composition from two distinct groups have been plotted, one group being from the second boiler disk from the outlet and the second being from all other disks where net boiling occurred. The variation of heat transfer rate with axial location, especially on the second disk, could probably be attributed to two reasons: the heat transfer coefficient changes with the increase of vapor quality in the direction of flow, a trend similar to results reported for pure potassium (8) and conventional fluids such as water (9); and the inaccuracy of tube wall temperature profile determination which reaches a peak at the second disk from the boiler outlet.

Surface Boiling

In forced convection boiling of a subcooled liquid the fluid generally undergoes surface boiling before the start of net boiling (net vapor generation). This can occur at any location where the heating surface temperature (inner tube wall) exceeds the saturation temperature. A major portion of the test section for all experiments fell in this region. The heat flux density q/A is again presented as a function of wall superheat ΔT in Figures 6 and 7. Although all data points are above the corresponding net boiling data as shown by the bottom line in each figure, these data exhibit considerable scatter. These data represent a partial boiling regime where both forced convection and boiling effects exist. No single correlation can be drawn owing to different degrees of subcool in forced convection contributions. The points for different axial locations are distinguished by different symbols in Figures 6 and 7. As can be seen the local heat flux densities are higher near the boiler entrance than near the net boiling region. This trend indicates the vapor concentration near the surface influences the heat transfer. The upper lines drawn in Figures 6 and 7 are indicative of the maximum values of heat flux density obtainable in these experiments. These heat flux densities for surface boiling are also found to be not higher than those for forced convection. This is considerably different from surface boiling of water (10), indicating that the boiling of amalgams requires high superheat and the improvement of heat transfer with surface boiling in tubes may be limited. Comparison of Figure 6 with 7 indicates the relative magnitude of surface boiling heat transfer rates to correspond to those for net boiling heat transfer; that is heat transfer rates for 14.7% K amalgams are consistently lower than those for 44.5% K amalgams.

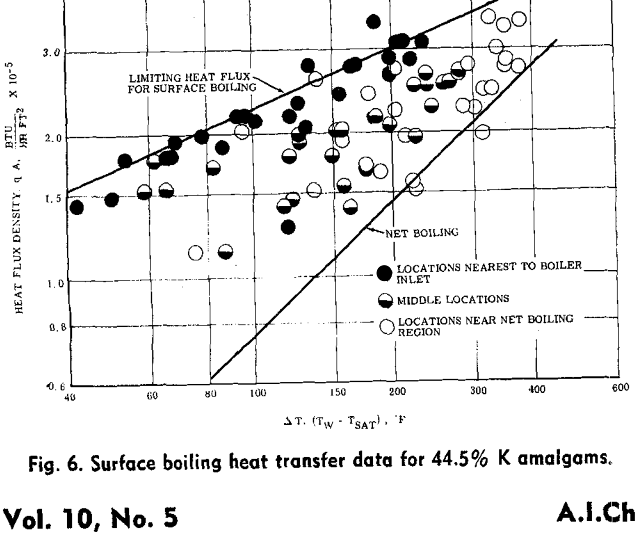

Fig. 6. Surface boiling heat transfer data for 44.5% K amalgams.

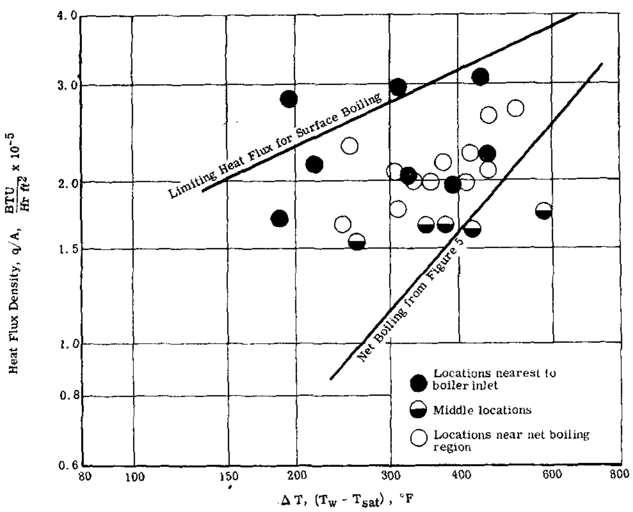

Fig. 7. Surface boiling heat transfer data for 14.7% K amalgams.

Heat-Transfer Coefficient Ratio (h_B/h_o)

The ratio of the boiling heat transfer coefficient to the nonboiling coefficient is commonly used for the correlation of data on forced convection boiling experiments. It indicates the improvement of heat transfer due to the boiling process. Wright, in correlating a large number of forced convection boiling water data, suggested that this ratio varied with a parameter which combined a modified boiling number N'_{Bo} and a function of Martinelli parameter X (11). The modified boiling number is expressed as

$$N'_{Bo} = (\rho_L/\rho_V)\ (N_{Bo}) = (\rho_L/\rho_V)\ (q)/(AG\lambda)$$

which is a measure of the effect of nucleate boiling in flow systems. The Martinelli parameter function $(X)^{-0.5}$ contributes the two-phase forced convection effect. The ratio (h_B/h_o) increases as the Wright parameter increases for boiling heat transfer with water. In the present experiments it was found that the boiling process in the tube generated a large per cent of vapor volume such that in-

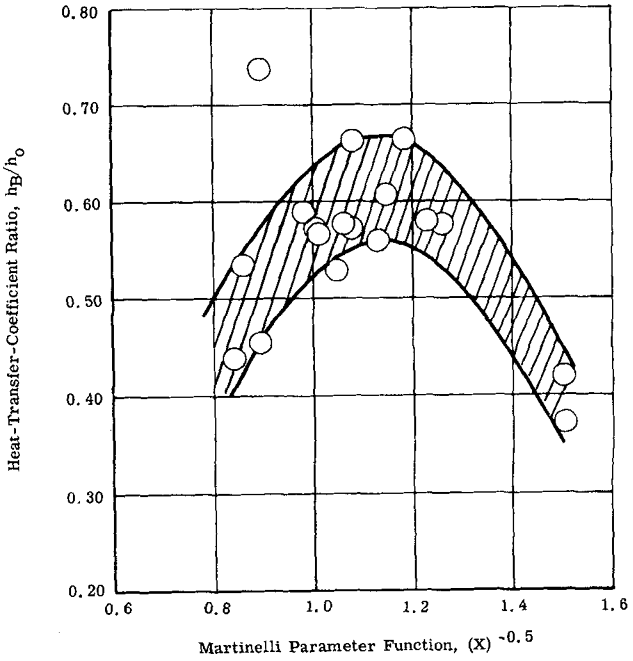

Fig. 8. Variation of ratio of heat transfer coefficients with Martinelli parameter function (N'_{BO} = 2.1 to 3.3).

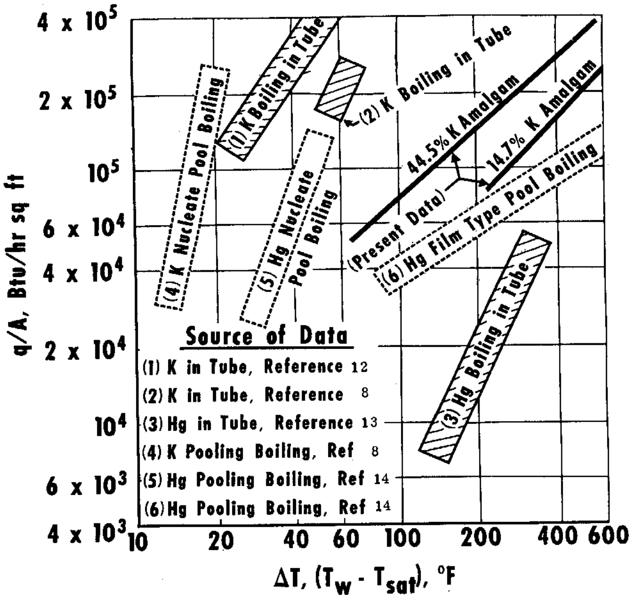

Fig. 9. Comparison of boiling heat transfer data for amalgams, mercury, and potassium.

creasing $(X)^{-0.5}$ beyond a certain point hindered the heat transfer. Figure 8 shows this effect for experiments with 44.5% K amalgams for a range of boiling number from 2.1 to 3.3 (near the boiler outlet). The trend is represented by the band indicated. Notice the boiling process actually reduced the heat transfer coefficient below the coefficient for single-phase forced convection. This vapor blanketing condition was conceivably aggravated by the size of the tube used. The influence of void fraction can not be overemphasized in the forced convection boiler design with liquid metals.

Comparison of Present Results with Pure Component Data

The net boiling heat transfer data for potassium amalgams are compared with those for pure potassium (*8, 12*) and mercury (*13*) reported in the literature (see Figure 9). Some discrepancies were noted in the literature concerning forced convection boiling mercury data. These were presumably due to the difference in wetting conditions. The present data for amalgams is bracketed between the data for these pure components, as indicated in Figure 9, with the boiling heat flux densities for the same ΔT increasing with potassium content. Also shown in Figure 9 are reported values for pool boiling with potassium and mercury (*14*). The difference in slope for the nucleate boiling curve vs. the film boiling curve suggests that the present data represent the mechanism of film boiling.

CONCLUSIONS

From the results presented in this paper the following conclusions can be drawn:

1. Net boiling heat transfer data in a vertical tube for 44.5 and 14.7% K amalgams are reported in a conventional correlation of (q/A) vs. $(T_W - T_{SAT})$. These data indicate that film boiling prevails. Comparison was made with forced convection boiling data for pure potassium and mercury from recent literature. Present data for amalgam lies between the two pure components with the heat flux density increasing with increasing potassium content.

2. Surface boiling of potassium amalgams in the vertical tube results in a heat transfer rate not significantly larger than the rate for net boiling or even forced convection heat transfer. Void fraction in the tube influences the rate of heat transfer.

3. Because of the void fraction effect on the forced convection boiling the critical heat flux depends on the size of the flow channel. Correlation of forced convection boiling data of amalgams in the range of present investigation require void fraction information. The method of correlation suggested by Wright for water systems (*11*) can not be applied.

NOTATION

A = heat transfer area, sq. ft.
D = diameter of test section, sq. ft.
G = mass flow velocity, lb./(hr.) (sq. ft.)
h_B = boiling heat transfer coefficient, B.t.u./(hr.) (sq. ft./°F.)
h_o = nonboiling heat transfer coefficient, B.t.u./(hr.) (sq. ft./°F.)
L = total length of test section, ft.
N_{Bo} = boiling number = $q/AG\lambda$, dimensionless
N'_{Bo} = modified boiling number $= N_{Bo}(\rho_L/\rho_V)$, dimensionless
P = pressure, lb./sq. in.
q = heat flux, B.t.u./hr.
T = temperature, T_W tube wall temperature and T_{SAT} saturation temperature, °F.
ΔT = wall superheat = $(T_W - T_{SAT})$, °F.
x = vapor quality, lb./lb.
X_{tt} = Martinelli parameter = $(\rho_V/\rho_L)^{0.5}$ $(\mu_L/\mu_V)^{0.1}$ $(1 - x/x)^{0.9}$, dimensionless

Greek Letters

ρ_L = liquid density, lb./cu. ft.
ρ_V = vapor density, lb./cu. ft.
μ_L = liquid viscosity, lb./(hr.) (ft.)
μ_V = vapor viscosity, lb./(hr.) (ft.)
α = void fraction, dimensionless
λ = heat of vaporization, B.t.u./lb.

LITERATURE CITED

1. Henderson, R. E., *Chem. Eng. Progr.*, **59**, No. 10, p. 56 (1963).
2. Ross, P. T., et al., paper presented at A.I.Ch.E. 50th National Meeting, Buffalo, New York (May, 1963).
3. Benjamin, J. R., and J. W. Westwater, "International Developments in Heat Transfer," Part II, Am. Soc. Mech. Engrs. (1961).
4. Bonilla, C. F., and C. W. Perry, *Trans. Am. Inst. Chem. Engrs.*, pp. 685-708 (1942).
5. Rose, W. J., H. L. Gilles, and V. W. Uhl, *Chem. Eng. Progr. Symposium Ser. No. 41*, **59**, (1963).
6. Scriven, L. E., *Chem. Eng. Sci.*, **10**, Nos. 1-2, pp. 1-13 (1959).
7. Roeder, A., and W. Morawictz, *Z. Electrochemie*, **60**, 6 (1956).
8. General Electric Company, "Alkali Metals Boiling and Condensing Investigations," First Quarterly Report, Contract No. NAS 3-2528 (July-Sept., 1962).
9. Toblevich, N. Yu, and B. A. Eremenko, *U.S. Atomic Energy Comm. Translation AEC-tr-4490* (1961).
10. Jiji, L. M., and J. A. Clark, *Am. Soc. Mech. Engrs. Paper 62-WA-202* (1962).
11. Wright, R. M., Ph.D. thesis, University of California Lawrence Radiation Laboratory, Berkeley, California (1961).
12. Hoffman, H. W., and A. I. Krakoviak, "Proceedings of 1962 High-Temperature Liquid-Metal Transfer Technology Meeting," U.S. Atomic Energy Comm. (1962).
13. Kutateladze, S. S., et al., "Liquid Metal Heat Transfer Media," Supplement No. 2, p. 109, Translation, Consultants Bureau, Inc., New York (1959).
14. Bonilla, C. F., et al., *Chem. Eng. Progr. Symposium Ser. No. 20*, **53**, 51 (1957).

Manuscript received August 28, 1963; revision received December 19, 1963; paper accepted December 20, 1963. Paper presented at A.I.Ch.E. Houston meeting.