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A LIQUID-METAL HEAT-TRANSFER EXPERIMENT

by

R. E. Holtz

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A LIQUID-METAL HEAT-TRANSFER EXPERIMENT

by

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Reactor Engineering Division

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NOMENCLATURE

A	Inside area of tube, ft^2
A_1	Outside heated area of tube, ft^2
A_2	Inside area of heating elements, ft^2
B	Magnet flux, gauss
D	Outside diameter of heated tube, ft
d	Inside diameter of heated tube, ft
E	Flowmeter output, millivolts
E_{b1}	Black-body emissive power of outside tube surface, Btu/hr-ft^2
E_{b2}	Black-body emissive power of heating elements, Btu/hr-ft^2
E_{bs}	Black-body emissive power of surroundings, Btu/hr-ft^2
K	Thermal conductivity of tube, $\text{Btu/hr-ft-}^\circ\text{F}$
K_2	Magnet pole face end-effect correction factor, ft
L	Heated length, ft
N	Number of thermal-radiation shields, dimensionless
Nu	Nusselt number, dimensionless
Pe	Peclet number, dimensionless
Pr	Prandtl number, dimensionless
Q	Volumetric flow rate, gpm
q	Heat conducted through the tube, Btu/hr
q''	Heat flux supplied to the liquid metal, Btu/hr-ft^2
$q_{1 \rightarrow 2}$	Net radiant heat exchange between heater and tube, Btu/hr
q_w''	Heat loss with thermal-radiation shields, Btu/hr
$q_{w/o}''$	Heat loss without thermal-radiation shields, Btu/hr
Re	Reynolds number, dimensionless
T_b	Bulk-fluid temperature, $^\circ\text{F}$
T_c	Room temperature, $^\circ\text{F}$
T_f	Fluid temperature, $^\circ\text{F}$
T_h	Temperature of heating elements, $^\circ\text{F}$
T_i	Local inside-tube-wall temperature, $^\circ\text{F}$
T_o	Local outside-tube-wall temperature, $^\circ\text{F}$
Y	Defined by Equation 5, gpm-gauss/mV
<u>Greek Letters</u>	
α	Average coefficient of thermal expansion of pipe, $\text{ft/ft-}^\circ\text{F}$
ϵ_1	Emissivity of outside-tube surface, dimensionless
ϵ_2	Emissivity of heater surface, dimensionless
ϵ_s	Emissivity of surroundings, dimensionless
ϵ_M	Eddy diffusivity for momentum transfer, ft^2/hr
ρ_f	Electrical resistivity of fluid, ohm-ft
ρ_w	Electrical resistivity of tube, ohm-ft
ν	Kinematic viscosity, ft^2/hr
σ	Stefan-Boltzmann's constant, $\text{Btu/hr-ft}^2\text{-}^\circ\text{R}^4$

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ABSTRACT

The utility of thermal-radiation heat transfer as a means of supplying and removing heat from a flowing liquid metal was experimentally investigated and found to be a satisfactory technique for this application.

Single-phase heat transfer to liquid NaK during vertical upflow in a tube was also examined. These experimental results are in fair agreement with the semiempirical expressions of R. N. Lyon and O. E. Dwyer.

The effect of the initiation of nucleate boiling in the system was also observed.

I. INTRODUCTION

Much effort is presently being extended to study the heat-transfer and fluid-flow characteristics of the liquid metals, especially the alkali metals and mercury. This effort is initiated because the successful design of liquid-metal-cooled reactors is dependent upon the availability of reliable heat-transfer and fluid-flow information. Since, at present, the fundamental mechanisms of boiling and condensing are not clearly understood, the design of boiling-heat-transfer equipment is basically an art and shall remain so until more of the fundamentals of boiling are discovered.⁽¹⁾

The primary objective of the Boiling Liquid Metal Program in the Reactor Engineering Division at Argonne is to obtain experimental information pertinent to the boiling-heat transfer and fluid-flow behavior of the alkali metals, especially sodium. Associated with obtaining this experimental information is the design of a heated section capable of supplying high, relatively uniform, heat fluxes to flowing liquid metals. Temperature up to and in many cases beyond 2100°F must be anticipated. The basic heat-transfer measurements to be taken in the heated section are the heat flux and the difference between the inside-tube-wall temperature and the fluid saturation temperature, and these measurements must be made as accurately as possible.

A variety of possible heating techniques has been examined, and thermal-radiation heating appears promising. To further examine thermal-radiation heat transfer as a means of supplying high, uniform, heat fluxes and removing heat, and to get acquainted with the hardware used in this type of work, a small-scale, thermal-radiation-heated, liquid-metal experiment with a small flow loop was conducted. It was also attempted to obtain as much single-phase and boiling-heat-transfer information as possible. Experience gained from the operation of this loop should enable the anticipation of some of the problems involved in the operation of more sophisticated, higher-temperature loops.

II. EXPERIMENTAL APPARATUS

A. General

A schematic diagram of the thermal-radiation heat-transfer loop is shown in Figure 1. The loop was constructed primarily from Type 316 stainless-steel tubing. Sodium-potassium alloy (NaK-78) was used as the heat-transfer fluid to enable these experiments to be done at lower temperatures and to eliminate the problems involved with the freezing of the liquid metal in case of a power failure, as would be the case with sodium.

Fig. 1

Schematic Diagram of Thermal-radiation Heat-transfer Loop

112-4951

The loop contained a 16-in.-long thermal-radiation-heated section. Radiation shields surrounded the heated section to reduce heat losses. Heat was removed from the loop by means of a cooling coil designed to remove heat by thermal radiation. An electromagnetic pump was used for circulating the NaK, and an electromagnetic flowmeter was used for obtaining flow rates. Chromel-Alumel thermocouples were employed to measure temperatures at key points in the system. The loop was pressurized by utilizing an argon gas blanket on the NaK surface in the supply tank.

The loop was contained within an evacuated enclosure. This enclosure was used as a safety precaution; in case of a rupture in the system, no injuries or fire would result. Also, the enclosure was necessary to extend the life of the tantalum heating elements used to supply heat by thermal radiation to the tube containing the flowing NaK. The enclosure with the cover on is shown in Figure 2.

112-3768

Fig. 2. Loop Enclosure

B. Loop Components

1. Thermal-radiation-heated Section

The thermal-radiation-heated section consisted of a 0.500-in.-OD, 0.035-in.-wall, Type 316 stainless-steel tube, containing flowing NaK. The tube was surrounded by two half-cylindrically-shaped tantalum elements, which were electrically heated. The 0.003-in.-thick tantalum

elements were $1\frac{1}{4}$ in. in diameter and had a heated length of 16 in. The heated section had a L/D ratio of 37. Al_2O_3 was used as both electrical and thermal insulation between the tantalum heating elements and the tube containing the flowing NaK. The Al_2O_3 insulation also supported and positioned the tantalum heating elements. Heat was transferred from the heating elements to the tube containing the flowing NaK by thermal radiation. The heat was then conducted through the tube wall to the liquid metal flowing inside the tube. The thermal-radiation heater before installation into the loop is shown in Figure 3.

112-3773

Fig. 3. Thermal-radiation
Heated Section

Three sheathed, Chromel-Alumel thermocouples were attached to the tube wall at the center of the heated length. These thermocouples consisted of 0.012-in.-diam wires, sheathed in a 0.060-in.-OD Inconel sheath and insulated from the sheath. One thermocouple was beaded at the outside tube wall. The other two thermocouples were unbeaded, each wire being individually spot-welded to the outside tube wall. These three thermocouples were brought into the heated section through holes in the bottom Al_2O_3 insulator.

Two Chromel-Alumel thermocouples were located both at the inlet and at the outlet of the thermal-radiation-heated section to measure the NaK temperature at these points in the loop.

Eight thermal-radiation shields surrounded the tantalum heating elements to reduce heat losses from the heated section. The cylindrically shaped, tantalum radiation shields were 0.003-in. thick and were spaced by means of short pieces of tantalum wire, which were spot-welded to the shields.

The thermal-radiation-heated section was contained within the evacuated enclosure; hence, conduction and convection effects between the tantalum heating elements and the tube containing the flowing NaK were insignificant. Since the L/D ratio of the thermal-radiation-heated section was large, the problem of radiation-heat transfer between the heating elements and the tube was approached as the heat exchange between two bodies of infinite

length. Thus, the problem was considered as the heat exchange between two gray, concentric, cylindrical surfaces of infinite length, each at a uniform temperature. If it is assumed that both surfaces radiate and reflect diffusely, the net heat exchange between the two surfaces can be expressed⁽²⁾ as

$$q_{1 \rightarrow 2} = \frac{A_1(E_{b1} - E_{b2})}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right)}. \quad (1)$$

The heat from the heating elements to the surroundings may be expressed as

$$q_w'' = \frac{1}{N+1} q_{w/o}'', \quad (2)$$

where

$$q_{w/o}'' = \frac{E_{b1} - E_{bs}}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_s} - 1}. \quad (3)$$

Equation (2) is valid for closely spaced shields that have equal emissivities. Figure 4 shows the effect that increasing the number of thermal-radiation shields has upon the amount of heat loss from the heated section.

Fig. 4

Effect of the Number of Thermal-radiation Shields upon Heat Loss

Since $E_{b1} = \sigma T_h^4$, $E_{b2} = \sigma T_0^4$, and $T_0 < T_h$, it is found that $E_{b2} \ll E_{b1}$ in Equation (1) (T_h and T_0 must be expressed in $^{\circ}R$ for calculation of E_{b1} and E_{b2}). Hence, the heat flux on the outside tube wall is nearly independent of the temperature distribution along the tube.

2. Auxiliary Heater

A resistance-heating wire was wound around the upper horizontal leg of the loop between the thermal-radiation heater and the cooling coil. The purpose of this heater was to initially heat the loop upon starting the system,

and to serve as a heat supply when the thermal-radiation heater was not in use. This resistance heater was capable of supplying 1 kW of power to the system. The advantage of having this auxiliary heater in the system was that this would enable the use of the thermal-radiation heater for test operation only; and the loop could be heated or cooled slowly by using the auxiliary resistance heater.

3. Thermal-radiation Cooling Coil

Heat was removed from the loop by thermal radiation from a coil containing the flowing NaK. The coil was constructed of 0.500-in.-OD, 0.035-in. wall, Type 316 stainless-steel tubing with a 6-in. coil diam and a 3-in. spacing between coils. The length of the tubing before boiling was 15 ft.

Figure 5, a photograph taken during the loop construction, shows the cooling coil welded into its position in the loop.

112-3767

Fig. 5. Loop Construction Picture

The coils were painted with high-temperature black paint to increase the emissivity (and absorptivity) of the Type 316 stainless-steel surface. The heat loss from the cooling coil (condenser) was then controlled by wrapping the coiled tube with foil. The painted stainless-steel surface had an emissivity of approximately 0.94.

4. Electromagnetic Pump

The electromagnetic pump used in this experiment is also shown in Figure 5. This pump had a maximum output in the range from 1 to 2 gpm. The copper windings were individually insulated with mica, and were also insulated from the Type 316 stainless-steel pump tube and the Armco iron pole pieces with mica.

5. Dump Tank

The dump tank (supply tank) was constructed of Type 304 stainless steel. Lines entering the dump tank consisted of the loop fill line, gas line, and dump-tank fill line. Two level probes were used to detect the NaK level during the dump-tank fill operation. The gas line was connected to both an argon gas supply and a vacuum pumping system to enable both a proper loop fill procedure and proper control of the system pressure during loop operation. A bellows in the loop fill line between the dump tank and the loop avoided any thermal expansion problems which may have occurred. Figure 5 shows a side view of the dump-tank exterior.

6. Argon Gas Supply

The argon gas supply and argon purification system is shown in Figure 6, which also shows the far side of the loop enclosure. The gas system consisted of a container of argon gas, a NaK bubbler, and NaK vapor traps. The argon gas was bubbled through the NaK in the NaK bubbler so that all impurities in argon gas that would react with NaK were removed before the gas entered the dump tank. The NaK vapor traps were used to trap any NaK vapor that may have been carried out of the NaK bubbler by the argon gas.

7. Loop Support

Because of possible thermal-expansion problems, it was necessary to have only one fixed support point in the loop. The electromagnetic pump was selected as the fixed point. The remainder of the loop, being above the electromagnetic pump, was supported by counterweighting at the top of the loop. As the temperature of the system increased, the loop was then free to expand upward.

The dump tank was connected to the loop through a bellows, eliminating the thermal-expansion problems in this area.

112-3772

Fig. 6. Gas Purification System

C. Instrumentation

1. Electromagnetic Flowmeter

Figure 5 also shows the electromagnetic flowmeter positioned in the system. The operating equation used with the flowmeter was⁽³⁾

$$Q = \frac{EY}{B}, \quad (4)$$

where Y may be expressed as

$$Y = \frac{1581}{DK_2} \left[1 + \alpha(T_f - T_c) \right] \left[D^2 + d^2 + \frac{\rho_f}{\rho_w} (D^2 - d^2) \right]. \quad (5)$$

The factor K_2 is the effect of the magnetic pole face length to the pipe inside diameter.

The magnet flux, B, was 1100 gauss $\pm 2\%$ between room temperature and 350°F.

Before being installed in the loop, the electromagnetic flowmeter was calibrated in a sodium test facility, built for testing electromagnetic flowmeters. With the magnet flux known, the calibration runs consisted of running a constant flow for a fixed period of time. The constant-millivolt output of the flowmeter and the weight of the sodium that passed through the Type 316 stainless-steel tube of 0.500-in. OD and 0.035-in. wall during the fixed time period were recorded. Thus, Y was determined for each calibration run by using Equation (4). Knowing the size and the electrical resistivity of the Type 316 stainless-steel tube and the thermophysical property data for liquid sodium,⁽⁴⁾ YK_2 was then calculated from Equation (5) for each test case. Combining this value of YK_2 from Equation (5) and the value of Y found from experiment, and utilizing Equation (4), K_2 was found for each run. The value of K_2 was 0.85 for all the calibration runs.

The K_2 value determined from the electromagnetic flowmeter calibration was then used in Equation (5) to determine the Y factor for the NaK system, which consisted of the same magnet, positioned in the same manner around a Type 316 stainless-steel tube of the same OD and wall thickness. Thus, by knowing B , calculating Y , and measuring the millivolt output, the NaK flow rate, Q , in the loop was found.

A further discussion and/or explanation as to the use of electromagnetic flowmeters are contained in Reference 3.

2. Thermocouples

Figure 7 shows the location of the Chromel-Alumel thermocouples which were positioned at various positions in the system. Two thermocouples at each of the more important temperature-measurement

Fig. 7. Diagram of Thermocouple Locations

positions assured a more accurate temperature reading. All the thermocouples were Chromel and Alumel wires, which were spot-welded to the outside tube surface. Except for the three thermocouples used to measure the outside tube-wall temperature in the heater section, all the thermocouple wire was No. 18 gauge. Four thermocouples were also spot-welded to the inside wall of the loop enclosure to assure a safe operating temperature of the enclosure.

The point of contact of each individual thermocouple wire with the tube wall was within 1/16 in. from the point of contact of the mating wire with the tube wall. Each thermocouple junction and the surrounding area were then packed with insulation so that the tube-wall temperatures would closely approximate the bulk temperature of the fluid. The thermocouples on the dump tank and the enclosure were attached in the same manner as the loop thermocouples.

Three thermocouples were located on the outside tube wall in the thermal-radiation-heated section. With the outside wall temperature and heat flux known, the inside wall temperature may be calculated from the expression,

$$q = \frac{2\pi KL(T_o - T_i)}{\ln(D/d)}$$

3. Other Instrumentation

A pressure gauge measured the pressure in the argon gas blanket. Control of the argon gas pressure on the NaK level in the dump tank was the technique used to control the loop pressure. This pressure gauge is shown in Figure 6.

Both a pressure gauge and a mercury manometer were used to measure the pressure in the evacuated loop enclosure. These two instruments are also shown in Figure 6.

The power supplied to both the thermal-radiation-heated section and the auxiliary heater was measured by utilizing a voltmeter and an ammeter. The voltmeter and ammeter were utilized in addition to the readout equipment that was furnished with the dc power supply.

4. Readout Equipment

The readout equipment used with the previously discussed instrumentation consisted of two potentiometers and two multipoint strip-chart recorders. The millivolt output of the electromagnetic flowmeter was read on one of the potentiometers. A selector switch was used with the other potentiometer so that the millivolt output of the thermocouples that indicated the outside-wall temperature, the heater-inlet temperature, and the heater-outlet temperature in the thermal-radiation-heated section could be monitored.

The output of the remaining thermocouples were read on the two multipoint strip-chart recorders. These recorders were calibrated to read the millivolt output of the Chromel-Alumel thermocouples in degrees Fahrenheit. The recorders had ranges of 0-2000°F and 0-800°F.

III. LOOP OPERATION AND RESULTS

A. Fill Procedure

After the entire system was assembled, the dump tank was filled with NaK. The procedure used to fill the dump tank was as follows: NaK from a large container was transferred to the evacuated glass container shown in Figure 8. The NaK was then moved from the glass container to the evacuated dump tank by pressurizing the NaK surface in the glass container with argon gas. The loop and the dump tank were evacuated to a vacuum of approximately 10^{-6} Torr before the fill with NaK. Since the system was evacuated prior to fill, the loop remained evacuated after the dump tank was filled with NaK.

112-4826

Fig. 8. Glass Container

The evacuated loop was filled with NaK from the dump tank by applying pressure on the liquid NaK surface in the dump tank. This pressure was applied by utilizing the argon gas blanket. The pressure control of the gas blanket in the dump tank also served as the method of controlling and maintaining the pressure in the loop during operation.

B. Operation and Performance

The thermal-radiation-heated loop was in operation from 6/1/64 through 1/31/65. During this period, three thermal radiation heaters operated a total of 750 hr. Of this time, approximately 500 hr of heater operation were used to obtain single-phase heat-transfer data, the remaining time being utilized to investigate boiling-heat transfer. Heat fluxes ranging up to 62,000 Btu/hr-ft² were investigated. Flow rates up to 416 lb/hr and liquid-metal temperatures up to 1400°F were obtained.

The first of the thermal-radiation heaters was operated for approximately 400 hr. During this period, heat fluxes up to 62,000 Btu/hr-ft² were obtained. Failure of this heating element occurred when sufficiently high temperatures caused the inside thermal-radiation shield to expand and come into contact with the power leads at the top of the heated section, causing a short circuit. The upper section of the inside shield then became excessively hot and began to melt. Part of the inside shield then fell against the upper part of the tantalum heating element, causing another short circuit and partial destruction of the tantalum heating element. A photograph of this heating element after failure occurred is shown in Figure 9. The deformation that the tantalum heating element had undergone before the failure is evident in this photograph.

The second and third tantalum heating elements were in operation 150 and 200 hr, respectively. Heat fluxes up to 30,000 Btu/hr-ft² were obtained with these heating elements. Failure of these heaters occurred because of embrittlement and flaking of the tantalum heating elements.

The first of the three tantalum heating elements operated at considerably higher temperatures than did the second and third heaters. The loop enclosure was evacuated, purged with argon gas, and then evacuated to a final vacuum of approximately 1 Torr before the initiation of loop operation in all cases; the enclosure pressure remained at 1 Torr or lower during operation. After 400 hr of operation at higher temperatures, the first of three tantalum heating elements retained its ductility; conversely, after significantly less time at lower temperatures, the other two heating elements were extremely brittle. The tantalum for all three heating elements was drawn out of laboratory stock; however, the tantalum for the first heating element and the thermal-radiation shields exhausted the present stock, and the tantalum was reordered. The tantalum that was used for making the latter two heating elements appeared to be of an inferior quality for this application; thus, embrittlement of the tantalum led to the eventual failure of these heating elements.

112-4147

Fig. 9. Thermal-radiation Heater after 300 hr of Operation

The other system components all performed satisfactorily. The thermal-radiating cooling coil proved a successful technique both for condensing the liquid metal vapors and for removing heat from a single-phase liquid metal. Additional foil was wrapped around the coil after loop operation was initiated so that the heat removed from the system would be reduced and higher fluid temperatures could be obtained.

C. Nonboiling Operation

1. Background Information

In a recent article, Dwyer⁽⁴⁾ discussed the heating and cooling of turbulent flowing liquids in circular tubes. A result of this analysis is

that the equation,

$$\text{Nu} = 7.0 + 0.025 \left[\text{Pe} - \frac{1.82 \text{Re}}{(\epsilon M/\nu)_{\max}^{1.4}} \right]^{0.8}, \quad (7)$$

can be utilized to estimate heat-transfer rates to liquid metals flowing in circular tubes under fully-established-flow and constant-heat-flux conditions. Equation (7) applies for Peclet numbers above the critical Peclet number. Below the critical Peclet number, it is recommended that the Nusselt number be assumed equal to 7.0. The critical Peclet number is defined as that Peclet number corresponding to the highest Reynolds number, for a given Prandtl number, at which heat is transferred by molecular conduction only.

The results of Lyon⁽⁵⁾ in an earlier study indicate that the semi-empirical relationship,

$$\text{Nu} = 7.0 + 0.025(\text{Pe})^{0.8}, \quad (8)$$

may be utilized for estimating heat-transfer coefficients under turbulent flow and uniform-heat-flux input conditions for liquid metals flowing in tubes.

Equations (7) and (8) are in fair agreement with each other. Recent data from BNL⁽⁶⁾ appear to be in reasonable agreement with both expressions.

Other investigators have reported lower results. Lubarsky and Kaufman⁽⁷⁾ have presented the expression,

$$\text{Nu} = 0.625 \text{Pe}^{0.4}, \quad (9)$$

for fully-developed turbulent-heat transfer to liquid metals flowing in tubes. Reference 8 discusses the effects that contribute to the disagreement of experimentally-measured, liquid-metal, heat-transfer coefficients.

In the laminar-flow region, the Nusselt number should equal 4.4.⁽⁴⁾ This is in agreement with the experimental results of Petukhov and Yushin.⁽⁹⁾

2. Discussion and Results

The data for single-phase NaK during vertical upflow in a tube with a uniform heat flux are tabulated in Appendix A. Using the measured heater inlet and outlet temperatures and flow rate, and the available thermo-physical property data for NaK,⁽¹⁰⁾ the total heat supplied to the liquid metal was calculated. This total heat input was then compared with the

total heat input from power measurements minus calculated losses. The total inputs supplied to the liquid metal by the thermal-radiation heater, as calculated by these two techniques, matched within $\pm 2\%$ for the data shown in the Appendix A. Using the known heater-inlet and heater-outlet temperatures and heat flux, and assuming a constant specific heat for the fluid, the bulk-fluid temperature was determined as a linear function of length along the vertical heater. Also, with the outside-wall temperature measured, and with the heat flux known, the inside-wall temperature was calculated from Equation (6).

Figures 10 and 11 show the data from this experiment and the results of Dwyer⁽⁴⁾ for estimating heat transfer to liquid metals flowing in circular tubes. Figure 10 plots Nusselt number versus Reynolds number, and Figure 11 plots Nusselt number versus Peclet number. The data points obtained from this experiment appear in agreement with the recommended prediction of Dwyer.

Fig. 10

Single-phase, NaK, Heat-transfer
Data: Nusselt Number vs Peclet
Number

112-4952

Fig. 11

Single-phase, NaK, Heat-transfer
Data: Nusselt Number vs Reynolds
Number

112-4953

An error analysis was performed to check the accuracy of the data obtained from this experiment. A maximum error in the Nusselt number

is estimated to be from ± 10 to $\pm 30\%$ for the square data points on Figures 10 and 11, and a maximum error ranging from ± 20 to $\pm 45\%$ is estimated for the round data points. The accuracy of the Reynolds numbers is estimated to be within $\pm 5\%$, and the Prandtl numbers are expected to be correct to $\pm 3\%$.

The accuracy of the Nusselt number calculated from experimental data is largely dependent upon accurate determination of the difference between the inside-wall temperature and the bulk-fluid temperature. In the determination of the possible error in calculating the Nusselt number, the possible sources of error considered were: heat flux, thermal conductivity of SS tubing, heater-inlet temperature, heater-outlet temperature, outside-wall temperature. In determining the accuracy of the Reynolds numbers, the accuracy to which the flow rate could be experimentally determined and the accuracy of the published thermophysical property data⁽¹⁰⁾ were considered. The accuracy of the thermophysical property data was also considered in determining the Prandtl numbers.

The data points shown in Figures 10 and 11 represent an average of two to six individual data points from Appendix A at which the flow rates and bulk-fluid temperatures were identical; thus, the Reynolds and Prandtl numbers were also identical. Average values of Prandtl, Reynolds, and Nusselt numbers for the data in Appendix A are shown in Appendix B. The spread of the individual data points used in determining each average value was within the experimental accuracy limits determined by the error analysis. The error analysis is discussed further in Appendix C.

Some of the earlier results, which showed the Nusselt numbers to be somewhat lower than predicted by Equations (7) and (8), may have been effected by nonwetting of the heat-transfer surface by the liquid metal. Recent data^(6,11) are in agreement with Equations (7) and (8).

D. Boiling Operation

Approximately 250 hr of heater operation were utilized to observe boiling. Boiling was obtained in the system by reducing the dump-tank pressure (below 10 psia) and supplying heat to the flowing NaK with both the vertical thermal-radiation heater and the horizontal auxiliary heater. Temperatures up to 1400°F were obtained before boiling. Qualities at the horizontal auxiliary heater outlet as high as 5% were obtained. The qualities were calculated using the flow rate of, and heat input to, the NaK passing through both the vertical and horizontal heaters. No pressure measurements other than the pressure in the dump tank were taken, and no wall-temperature measurements in the horizontal heated section were obtained. Hence, no definitive boiling-heat-transfer information was obtained, other than the observation of boiling and its effects.

The first indication of boiling in the loop was the occurrence of a "bumping" sound from the loop. Along with the "bumping" was the initiation of flow instabilities, which were detected by reading the millivolt output of the electromagnetic flowmeter on a potentiometer. A heat balance on the fluid passing through the heaters also indicated that boiling was taking place.

No definitive results as to the liquid superheats required to initiate nucleate boiling were obtained. However, it was observed that upon the initiation of boiling ("bumping" and flow instabilities), the temperature at the horizontal-heater outlet decreased (approximately 200°F).

These observations taken during boiling operation are in agreement with the observations of other investigators.⁽¹²⁾

IV. DISCUSSION AND CONCLUSIONS

A. Thermal-radiation Heating

The operation of the thermal-radiation heater has shown the feasibility of thermal-radiation techniques for supplying fairly high and uniform heat fluxes to a high-temperature liquid metal. However, several improvements and/or refinements can be made to improve the utility of a thermal-radiation-type heater for this application.

Figure 9 shows the first of the thermal-radiation heaters after 400 hr of operation. It is apparent that stresses due to forming of the tantalum into the half-cylinder shapes have caused some deformation of these heating elements. This problem may be overcome by replacing the two half-cylinder-shaped elements with closely spaced parallel wires.

Another refinement that may be utilized is the use of a thick wall in the flow tube, along with a relatively small flow passage. This will enable the obtaining of high heat fluxes at the inside tube wall, when considerably lower heat fluxes are applied to the outside tube wall. Another advantage of utilizing a thick-walled tube is that holes for thermocouples may be drilled in the wall, enabling the measurement of temperatures at known radial locations in the wall. This will enable determination of the temperature gradient across the wall, from which both the heat flux and the inside-wall temperature may be found. The utility of this technique is enhanced by the possibility of letting the outside wall be at rather high temperatures (approaching the melting point of the metal), while the inside section of the thick-walled tube retains its strength because of its lower temperature.

B. Single-phase Liquid-metal Heat Transfer

The data for a single-phase liquid flowing upward in a vertical tube under constant heat-flux conditions shows agreement with the expressions

presented by Dwyer⁽⁴⁾ and Lyon.⁽⁵⁾ Most of the data shown in this report were taken at lower temperatures. The data taken at higher temperatures also showed fair agreement with Equations (7) and (8); however, the error analysis applied to much of the higher-temperature single-phase data showed possible errors up to $\pm 80\%$. This large possible error in the higher-temperature data considerably reduces their usefulness. However, the lower-temperature data (shown in Appendix A and averaged in Appendix B) add credibility to Equations (7) and (8).

C. Boiling of Liquid Metals

The boiling observations in this investigation have resulted in the same basic conclusions as that of other investigators.⁽¹²⁾ It was observed that the initiation of boiling at low pressures (less than one atmosphere) is generally accompanied by a "bumping" noise and flow instabilities.

It is desirable to obtain sufficient boiling-liquid-metal, heat-transfer and fluid-flow information so that reliable empirical-type correlations can be formulated to predict the behavior of the liquid metals for use in reactor design applications. At present, such boiling-liquid-metal information is not available, primarily because of the many problems caused by unstable loop behavior and the lack of proper instrumentation for the high-temperature liquid-metal applications. The flow instabilities associated with boiling in the liquid metals at low pressures should be decreased significantly by the use of proper orificing techniques in the flow loop. Also, operating the system at higher pressures should reduce flow instabilities, because of the decreasing ratio of vapor density to liquid density with increasing temperature. Instrumentation for the accurate measurement of temperatures, pressures, void fractions, etc., in high-temperature liquid-metal systems is essential. Thus, it appears that much effort should be expended in the design and proving of sufficient instrumentation so that sufficiently accurate information may be obtained.

APPENDIX A

Single-phase Heat-transfer Data

Run No.	Flow (lb/hr)	T _b (°F)	Heat Flux (Btu/hr-ft ²)	Pr	Re	Pe	Nu
A1	210	775.2	4673	0.0079	14100	111.4	7.28
A2	210	827.3	11839	0.0074	14100	104.3	7.26
A3	210	852.1	20706	0.0072	14100	101.5	5.72
A4	210	852.0	20706	0.0072	14100	101.5	4.90
A5	210	885.5	25997	0.0070	14100	98.7	6.00
A6	210	887.1	25997	0.0070	14100	98.7	6.00
B1	67.7	265.6	3674	0.017	2133	36.3	7.08
B2	67.7	267.1	3411	0.017	2133	36.3	6.59
B3	67.7	267.0	3945	0.017	2133	36.3	5.07
C1	68.9	351.0	5347	0.0145	2501	36.3	6.59
C2	68.9	355.2	5347	0.0145	2501	36.3	6.59
C3	68.9	357.7	5881	0.0145	2501	36.3	4.35
D1	72.3	410.6	6157	0.0128	3232	41.4	7.34
D2	72.3	410.5	6439	0.0128	3232	41.4	5.81
D3	72.3	412.5	6439	0.0128	3232	41.4	7.75
E1	72.1	468.2	8129	0.0117	3223	37.7	7.20
E2	72.1	468.2	8407	0.0117	3223	37.7	4.96
E3	72.1	468.3	8683	0.0117	3223	37.7	4.40
F1	71.4	508.1	11079	0.0110	3192	35.1	4.91
F2	71.4	514.9	9974	0.0110	3192	35.1	7.06
F3	71.4	514.7	10250	0.0110	3192	35.1	5.21
G1	69.4	550.7	12093	0.0104	3297	34.3	7.13
G2	69.4	554.2	13180	0.0104	3297	34.3	5.84
G3	69.4	554.7	13439	0.0104	3297	34.3	5.29
H1	64.0	590.0	14875	0.0099	3290	32.7	5.19
H2	64.0	594.3	14389	0.0099	3290	32.7	6.26
H3	64.0	590.6	15374	0.0099	3290	32.7	4.87
I1	63.2	624.1	17845	0.0094	3248	30.6	6.21
I2	63.2	626.2	17845	0.0094	3248	30.6	6.90
I3	63.2	625.7	18324	0.0094	3248	30.6	6.38
J1	35.3	641.6	20665	0.0092	1814	16.7	5.15
J2	35.3	631.4	22195	0.0093	1814	16.9	4.07
J3	35.3	620.0	24518	0.0094	1814	17.0	5.32
K1	27.9	592.1	24075	0.0099	1434	14.2	4.65
K2	27.9	583.2	25286	0.0099	1434	14.2	5.18
K3	28.3	580.9	26989	0.0099	1455	14.4	5.52

Run No.	Flow (lb/hr)	T _b (°F)	Heat Flux (Btu/hr-ft ²)	Pr	Re	Pe	Nu
L1	20.8	518.5	24625	0.0110	930	10.2	3.84
L2	20.8	510.5	26194	0.0110	930	10.2	3.86
L3	20.8	507.0	26589	0.0110	930	10.2	5.23
M1	18.7	480.3	30827	0.0115	836	9.61	4.79
M2	18.7	475.5	31206	0.0115	836	9.61	4.85
M3	18.7	475.5	31206	0.0115	836	9.61	5.32
M4	18.7	472.0	31414	0.0115	836	9.61	5.11
N1	18.1	475.4	34572	0.0115	809	9.30	5.16
N2	18.1	475.4	34572	0.0115	809	9.30	5.00
O1	33.0	622.6	35934	0.0094	1696	15.9	3.91
O2	29.1	592.1	37251	0.0099	1496	14.8	3.82
O3	27.0	576.0	36635	0.0099	1388	13.7	3.78
P1	62.0	708.0	23924	0.0085	3670	31.2	8.15
P2	60.0	726.3	26693	0.0083	3552	29.5	6.50
P3	60.0	726.1	27120	0.0083	3552	29.5	6.17
P4	60.0	730.7	26693	0.0083	3552	29.5	5.69
P5	60.0	731.4	27243	0.0083	3552	29.5	5.81
Q1	53.6	722.6	24534	0.0083	3173	26.3	9.81
Q2	48.1	712.1	33664	0.0084	2848	23.9	7.65
Q3	48.2	710.9	34043	0.0084	2853	24.0	8.92
R1	410	618.2	6080	0.0095	21400	203	10.06
R2	410	617.7	6080	0.0095	21400	203	6.70
R3	410	619.5	5470	0.0095	21400	203	9.05
S1	132	662.4	5420	0.00875	7200	64.4	5.87
S2	132	661.5	5620	0.00875	7200	64.4	7.30
S3	132	662.4	5420	0.00875	7200	64.4	7.04
T1	222	670.8	5900	0.00885	12200	108	5.98
T2	222	670.8	5900	0.00885	12200	108	5.98
T3	222	670.5	5900	0.00885	12200	108	7.97
U1	315	675.0	4650	0.00880	17500	154	6.04
U2	315	675.5	4650	0.00880	17500	154	7.55
U3	315	675.5	4650	0.00880	17500	154	7.55
V1	413	679.0	4870	0.00875	22900	200	7.91
V2	413	679.0	4870	0.00875	22900	200	6.33
V3	413	679.0	4870	0.00875	22900	200	6.33
W1	129	708.0	5680	0.0084	7440	62.5	6.05
W2	129	708.3	5680	0.0084	7440	62.5	6.05
W3	129	708.5	5870	0.0084	7440	62.5	7.49

Run No.	Flow (lb/hr)	T _b (°F)	Heat Flux (Btu/hr-ft ²)	Pr	Re	Pe	Nu
X1	221	719.5	5520	0.0083	12900	107	7.04
X2	221	720.5	5520	0.0083	12900	107	7.04
X3	221	720.5	5520	0.0083	12900	107	7.04
Y1	304	724.0	6060	0.0083	17700	147	6.44
Y2	304	724.0	6060	0.0083	17700	147	6.44
Y3	304	724.1	6060	0.0083	17700	147	7.73
Z1	404	727.5	6510	0.0082	23700	194	8.31
Z2	404	728.5	5920	0.0082	23700	194	7.55
Z3	404	728.5	5920	0.0082	23700	194	7.55
AA1	131	769.5	5950	0.00785	8240	64.7	5.38
AA2	131	770.7	6140	0.00785	8240	64.7	6.42
AA3	131	771.5	5570	0.00785	8240	64.7	7.00
BB1	218	782.0	6770	0.00775	13700	106	7.08
BB2	218	782.0	6770	0.00775	13700	106	7.08
BB3	218	782.0	6770	0.00775	13700	106	7.08
CC1	312	788.2	6210	0.0077	21800	167	9.74
CC2	312	787.5	6600	0.0077	21800	167	10.35
CC3	312	788.2	6210	0.0077	21800	167	9.74
DD1	401	793.2	7060	0.0077	28000	216	10.08
DD2	401	792.5	7560	0.0077	28000	216	11.87
DD3	401	793.2	7060	0.0077	28000	216	10.08

APPENDIX B

Average of Single-phase Heat-transfer Data

Series of Runs	Re	Pe	Nu
A1-A6	14100	102.7	6.19
B1-B3	2133	36.3	6.25
C1-C3	2501	36.3	5.84
D1-D3	3232	41.4	6.48
E1-E3	3223	37.7	5.52
F1-F3	3192	35.1	5.73
G1-G3	3297	34.3	6.09
H1-H3	3290	32.7	5.44
I1-I3	3248	30.6	6.50
J1-J3	1814	16.9	4.85
K1-K3	1441	14.3	5.12
L1-L3	930	10.2	4.31
M1-M4	836	9.61	5.02
N1-N2	809	9.30	5.08
O1-O3	1527	14.8	3.83
P1-P5	3576	29.8	6.46
Q1-Q3	2960	24.7	8.79
R1-R3	21400	203	8.60
S1-S3	7200	64.4	6.74
T1-T3	12200	108	6.64
U1-U3	17500	154	7.05
V1-V3	22900	200	6.85
W1-W3	7440	62.5	6.53
X1-X3	12900	107	7.04
Y1-Y3	17700	147	6.87
Z1-Z3	23700	194	7.80
AA1-AA3	8240	64.7	6.27
BB1-BB3	13700	106	7.08
CC1-CC3	21800	167	9.95
DD1-DD3	28000	216	10.68

APPENDIX C

Error Analysis

A. Nusselt Number

1. Heater-inlet Temperature

The heater-inlet temperature was measured 2 in. below the heater inlet. The temperature was measured with two Chromel-Alumel thermocouples, and their millivolt outputs were read on a potentiometer. Radiation heat transfer from the tube between the location of the thermocouples and the heater inlet was accounted for. Since the two thermocouples were from select wire, and their millivolt outputs were in excellent agreement with each other (± 0.01 mV) during loop operation from which the data in Appendix A were obtained, the following possible errors in the measurement of the heater inlet temperature were estimated:

Up to 500°F	$\pm 0.40^\circ\text{F}$;
From 500 to 800°F	$\pm 0.50^\circ\text{F}$;
From 800 to 900°F	$\pm 0.70^\circ\text{F}$;
From 900 to 1000°F	$\pm 1.00^\circ\text{F}$;
From 1000 to 1100°F	$\pm 1.30^\circ\text{F}$.

2. Heater-outlet Temperature

The heater-outlet temperature was measured $3\frac{1}{2}$ in. above the heater outlet by reading the millivolt outputs of two Chromel-Alumel thermocouples on a potentiometer. Location of the thermocouples at this position enabled the fluid to reach a uniform temperature profile at the point of measurement. This measurement technique was identical to the measurement of the heater-inlet temperature; hence, the same possible errors in measurement of the heater-outlet temperature as were estimated for the heater-inlet temperature were applied.

3. Outside Heater-wall Temperature

The outside heater-wall temperature was measured by two Chromel-Alumel thermocouples, which had each lead individually spot-welded to the wall, and by one Chromel-Alumel thermocouple, which was beaded at the wall. These thermocouples were precalibrated before using the thermal-radiation heater. During loop operation, the beaded thermocouple yielded higher millivolt readings than did the two thermocouples that had individual wires spot-welded to the wall. The temperatures measured with the thermocouples that had the individual wires spot-welded to the wall were utilized for obtaining the outside-wall temperature. The millivolt

outputs from these thermocouples were also read on a potentiometer and showed excellent agreement with each other. The possible errors of these thermocouple measurements were also estimated to be the same as those for the heater-inlet temperature.

4. Heat Flux

The heat flux found by using the measured heater-inlet and -outlet temperatures and flow rate, and the available thermophysical property data for NaK, matched the heat flux found from power measurements, less calculated heat losses and end effects, within $\pm 2\%$ for the data found in Appendix A. Hence, it was estimated that the possible error in the heat flux found from an energy balance was accurate within $\pm 2\%$. Approximately 15% of the total power generated in the heating elements was lost from the heated section.

5. Thermal Conductivity of Tube Wall

The thermal conductivity of the Type 316 stainless-steel tube, as found in the literature of several manufacturers, appears to be in excellent agreement. It was estimated that the thermal conductivity was known within $\pm 2\%$.

B. Reynolds Number

In calculation of the possible error in the Reynolds number, it was estimated that the flow rate was accurate within $\pm 4\%$. It was also estimated that the thermophysical property data (density and dynamic-viscosity) in Reference 10 were accurate to within $\pm 1\%$.

C. Prandtl Number

In the calculation of the Prandtl number, it was also estimated that the thermophysical property data from Reference 10 (specific heat and thermal conductivity) were accurate to within $\pm 1\%$.

D. Sample Calculation

Run A-6 (in Appendix A) will be utilized for the sample calculation. The amount of the possible estimated error will be designated by the absolute-value indication, accompanied by the subscript e. The following data were either measured or calculated from Run A-6:

$$T_b = 887.1^\circ\text{F};$$

$$q'' = 25997 \text{ Btu/hr-ft}^2;$$

$$T_i - T_b = 10.2^\circ\text{F};$$

$$\text{flow} = 210 \text{ lb/hr};$$

$$\text{Nu} = 6.00;$$

$$\text{Pr} = 0.0070;$$

$$\text{Re} = 14100;$$

and

$$\text{Pe} = 98.7.$$

Since the bulk-fluid temperature, T_b , may be expressed as

$$T_b = \frac{T_{\text{inlet}} + T_{\text{outlet}}}{2},$$

and

$$|T_b|_e = \frac{|T_{\text{inlet}}|_e + |T_{\text{outlet}}|_e}{2},$$

the possible error in the calculation of the bulk-fluid temperature is

$$|T_b|_e = \frac{(\pm 0.7^\circ\text{F}) + (\pm 0.7^\circ\text{F})}{2} = \pm 0.7^\circ\text{F}.$$

The possible error in the outside-wall temperature is

$$|T_o|_e = \pm 0.7^\circ\text{F}.$$

Equation (6) may be written as

$$\left[\frac{2\pi K L}{\ln(D/d)} \right] (T_o - T_i) = q.$$

But

$$q = q'' A = q'' \pi d L.$$

Hence, Equation (6) may also be written,

$$T_o - T_i = \frac{d}{2} \ln(D/d) \frac{q''}{K}.$$

But

$$|q''|_e = \pm 2\%$$

and

$$|K|_e = \pm 2\%;$$

hence,

$$|T_0 - T_i|_e = \pm 4\%(T_0 - T_i).$$

Since

$$T_0 - T_i = \frac{D_i}{2} \ln(D/d) \frac{q''}{K} = 5.80^\circ\text{F for Run A-6,}$$

$|T_0 - T_i|_e$ is

$$|T_0 - T_i|_e = (T_0 - T_i)(\pm 0.04) = \pm 0.23^\circ\text{F}.$$

Thus, the possible error in obtaining the inside-wall temperature is the sum of the possible error in measuring T_0 and the error caused in calculating the temperature drop through the tube wall. This error is

$$|T_i|_e = (\pm 0.7^\circ\text{F}) + (\pm 0.23^\circ\text{F}) = \pm 0.93^\circ\text{F}.$$

Since $T_i - T_b = 10.2^\circ\text{F}$ for Run A-6, and T_i is accurate to within $\pm 0.93^\circ\text{F}$, and T_b is accurate to within $\pm 0.70^\circ\text{F}$, the error limits in finding $(T_i - T_b)$ is

$$|T_i - T_b|_e = (\pm 0.93^\circ\text{F}) + (\pm 0.7^\circ\text{F}) = \pm 1.63^\circ\text{F}.$$

The percent error is

$$|T_i - T_b|_e = \frac{\pm 1.63}{10.2} = 16.0\%.$$

The Nusselt number may be expressed as

$$\text{Nu} = \frac{dq''}{K(T_0 - T_i)},$$

and the percent error in calculating the Nusselt number may be found. Since

$$\text{Nu} = \frac{(d)(q'' \pm 2\%)}{(K \pm 2\%)[(T_w - T_0) \pm 16.0\%]}$$

the possible error in calculating the Nusselt number is approximately

$$|\text{Nu}|_e = 20.0\%.$$

The possible errors in the Reynolds number and Prandtl number are

$$|Re|_e = \pm 5\%,$$

and

$$|Pr|_e = \pm 3\%.$$

Hence, the possible error in the Peclet number is

$$|Pe|_e = \pm 8\%.$$

E. Discussion of Error Analysis

The most significant source of error is in the calculation of the Nusselt number. In this analysis, the accuracy to which the heater-inlet temperature, heater-outlet temperature, and heater-wall temperature could be obtained was the largest source of error in determining the accuracies of the data that were obtained. All these readings were taken on potentiometers to minimize any errors due to the reading of instruments. The thermocouples in the system were of select wire, and were thermocycled (aged) and precalibrated before loop operation. Two thermocouples were utilized to obtain temperatures at each of these key locations. The millivolt outputs of the two thermocouples at each location were in excellent agreement with each other (within the limits of ± 0.01 mV) during the runs from which usable data were obtained.

Several times during the operation of the system, the millivolt outputs of the thermocouples at a location exceeded the limits of ± 0.01 mV. These runs were discarded. If this difference in thermocouple readings persisted or increased, the loop was shut down, the thermocouples were inspected, and the necessary repairs were made.

The accuracy limits assumed for the Chromel-Alumel thermocouples are somewhat better than generally expected with thermocouples. However, due to the use of select thermocouple wire, the thermocouple precalibration, the use of potentiometers for readout equipment, and the excellent agreement of the two thermocouples at each location, the assumed high accuracy appears justified.

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