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A SYSTEM FOR MEASURING THE HEAT TRANSFER COEFFICIENT OF LIQUID SODIUM IN A THERMAL ENTRANCE REGION

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A SYSTEM FOR MEASURING THE HEAT TRANSFER COEFFICIENT

OF LIQUID SODIUM IN A THERMAL ENTRANCE REGION

Approved:

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SUMMARY

The purpose of this thesis was to design and construct a system for the experimental determination of the heat transfer coefficient of liquid sodium in a thermal entrance region.

A review of the literature revealed that analytical and experimental investigations of entrance region phenomena had been conducted for a variety of fluids. In quest of higher rates of heat transfer, much attention has recently been given to liquid metals as possible heat transfer media. Quite often experimental data for these fluids have been found to be lower than theoretical predictions. In particular, two previous works dealing with the heat transfer coefficient of liquid sodium in an entrance region reported results which were erratic and lower than expected. The phenomena of wetting between a liquid-solid interface has been suggested as a possible cause for the variation in experimental measurements. However, the actual effects of wetting on heat transfer are not definitely known. One case in which a non-wetting condition between sodium and stainless steel was known to exist was reported with no effect of wetting on heat transfer. Some tests have been made with liquid metals in which the data indicated a definite decrease in the heat transfer coefficient due to non-wetting, while others have shown that there was little variation in results between wetting and non-wetting. The effects of wetting are believed to be more pronounced in an entrance region, where coefficients are higher, and in flow passages of small diameter, where a small thermal resistance would be magnified. A system is therefore described in which

the heat transfer coefficient at a sodium-copper interface with a small length-to-diameter ratio could be measured. Since sodium is used commercially to deoxidize copper at high temperature, it is believed that a wetting condition could be obtained merely by raising the interface temperature. When wetting existed, the measured heat transfer coefficient should closely approximate predictions of the theoretical analogy.

Three analytical results are presented which could be used in comparison with experimental data obtained by the test apparatus described. The solutions differ only in the postulated velocity distribution. They are as follows: (1) the solution by Graetz for parabolic velocity profile, (2) the solution by Graetz for uniform velocity distribution, and (3) the solution by Poppendiek and Palmer for velocity distribution obeying the 1/7 power law.

Since experimental results are to be compared with the above solutions, the test section must be designed to approximate closely the postulates inherent in the solutions. These are as follows: (1) fluid temperature is uniform upstream of the test section, (2) heat is added to the fluid only at the copper-sodium interface, (3) longitudinal heat conduction is negligible, and (4) the temperature of the copper-sodium interface is constant. A method for computing longitudinal conduction and heat addition to the sodium other than at the test surface is given in the appendix.

The complete system was assembled and loaded with sodium. The initial test section and pump both failed to operate. These parts were replaced, but still no data could be taken due to the formation of insoluble oxides during modification of the equipment. The apparatus was then dismantled, cleaned, and inspected.

The final test section built for the present system is believed to be suitable for measuring entrance region coefficients at elevated interface temperatures. The design introduces a considerable deviation from theoretical postulates; however, a closer approximation employing a heat insulating gasket was found impossible.

Recommendations are made for a system which it is believed would operate satisfactorily. The test section used could be similar to the final one described in this thesis. The pumping problem could be solved by trying several models, or it could be completely eliminated by circulating sodium with gas pressure. Other recommendations concerning the arrangement of equipment and precautions for keeping the sodium free of contamination are also made.

CHAPTER I

INTRODUCTION

General.--One of the greatest challenges in the field of power generation has been the redesign of heat exchange equipment to obtain higher rates of heat transfer more efficiently and with smaller surface areas. The challenge has been accepted by many investigators, and great improvements have been made in heat exchangers over the years. The results of their works are the high performance pieces of equipment found in a wide variety of modern industries.

There have been two recent developments in the field which may permit phenomenal rates of heat transfer compared with values used in the design of present equipment. One of these is the use of liquid metals, which have high thermal conductivities, as heat transfer media. The other development is a more effective use of the high heat transfer coefficients associated with a thermal entrance region.

A thermal entrance region occurs when a thermally established fluid flows past a discontinuity in the thermal boundary conditions. The discontinuity could be in the form of a sudden change in either temperature or heat flux of the wall of a tube through which the fluid is flowing. In either case the heat transfer coefficient at the discontinuity can be shown to be infinite. When a viscous fluid flows through a tube, the fluid near the wall will be in laminar motion. The mode of heat transfer near the wall is then by molecular conduction only. The heat transferred across the solid-fluid interface can be expressed by the following equation:

$$\left.\frac{q}{A}\right]_x = h_x\,(t_w - t_m)_x = -k\left.\frac{\partial t}{\partial y}\right]_{(x,\,0)} \qquad (1)$$

In this case, $\frac{q}{A}$ is the heat flux per unit area of the interface, h is the heat transfer coefficient, t_w is the tube wall temperature, t_m is the mixed mean fluid temperature, k is the thermal conductivity of the fluid, $\frac{\partial t}{\partial y}$ is the temperature gradient of the fluid, x is the direction of flow with x = 0 at the discontinuity, and y is the direction normal to the direction of flow with y = 0 at the wall. Equation 1 may be rearranged to solve for the heat transfer coefficient as

$$h_x = \frac{-k\left.\frac{\partial t}{\partial y}\right]_{(x,\,0)}}{(t_w - t_m)_x} \qquad (2)$$

The following postulates are made: (1) a fluid of uniform temperature flows through a channel having the same wall temperature and (2) at the position x = 0 the temperature of the wall is suddenly changed to a new value which is held constant for all x greater than zero. The temperature gradient, $\frac{\partial t}{\partial y}$ (x, 0), can then be shown to approach infinity as x approaches zero. Since $(t_w - t_m)_x$ is finite at x = 0, the heat transfer coefficient is infinite.

For the case of a heat flux discontinuity the assumptions are as follows: (1) a fluid of uniform temperature flows through a tube with the same wall temperature and (2) a heat flux is imposed at x = 0 which is held constant for all x greater than zero. Then $(t_w - t_m)$ at x = 0 is zero. However, $\frac{\partial t}{\partial y}$ (x, 0) has a finite value; hence the heat transfer coefficient is again infinite at x = 0.

By using a liquid metal as a heat transfer medium and taking advantage of the high coefficients obtained in an entrance region, the design of heat exchangers with very high rates of heat transfer should thus be possible. However, complications have been noted with liquid metal systems which often make accurate predictions of heat transfer coefficients impossible. One of the greatest uncertainties is the effect of wetting on the heat transfer coefficient between liquid metal and a solid interface.

Previous work.--There has been very little work done on the topic of heat transfer to liquid metals in a thermal entrance region with constant wall temperature. However, the theoretical effects of an entrance region have been known for many years; and recently considerable work has been done on heat transfer to various fluids in an entrance region with constant wall temperature or constant heat flux.

The earliest known work which could be adapted to an entrance region is the mathematical solution of Graetz (1)[1] published in 1883 for forced convection heat transfer to a fluid flowing through a tube with uniform velocity distribution. Graetz (2) also developed an equation for fluid in laminar flow in a tube which was published in 1885.

The next important work was not until 1921 when Latzko (3) presented a solution for heat transfer in a thermal entrance region for a fluid in turbulent flow. He postulated a Prandtl modulus of one and neglected the contribution of molecular conduction to heat transfer.

In 1928 Leveque (4) derived a solution which is used as an asymptotic solution to the equation of Graetz for parabolic velocity

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[1]Numbers in parentheses refer to references in the bibliography.

distribution of a fluid very near the beginning of a thermal entrance region.

In 1946 Sanders (5) presented a solution for a fluid with a fully established velocity distribution in an entrance region of constant wall temperature. His solution is applicable only for fluids of high Prandtl modulus.

Boelter, Young, and Iversen (6) made experimental investigations of local heat transfer coefficients to air with a uniform wall temperature. Values for a wide variety of simultaneous hydrodynamic and thermal entrance conditions were obtained. The range of Reynolds modulus was from 17,000 to 56,000.

Humble, Lowdermilk, and Desmon (7) made an investigation of average heat transfer and friction coefficients with air flowing through smooth tubes. The ratios of $\frac{L}{D}$[2] used were 15 to 120. Their results and related N.A.C.A. research is summarized by Pinkel (8).

Seban and Shimazaki (9) presented numerical solutions for fluids of high thermal conductivity in a thermal entrance region of uniform wall temperature. Their calculations included the contribution of eddy diffusivity. Later Seban (10) performed an experimental investigation of the heat transfer coefficient to lead-bismuth entectic in a tube of approximately constant heat flux. Both local coefficients in the entrance region and average coefficients for the tube length were obtained.

English and Barrett (11) obtained experimental values of the local heat transfer coefficient between mercury and a stainless steel tube with a constant wall heat flux. Interest was largely placed on the

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[2] Symbols used are defined in Appendix A.

average coefficient; however, their data could be applied to the entrance region.

Poppendiek (12) developed a theoretical solution for the Nusselt modulus of a fluid in turbulent flow between parallel plates in a thermal entrance region with a constant wall temperature. The contribution of eddy diffusivity to heat transfer was neglected. The solution can be applied to the initial portion of an entrance region of a circular pipe as the flow annuli near the pipe wall are the important heat transfer layers and may be treated as the flow layers between parallel plates. Poppendiek and Palmer (13) later presented an asymptotic solution to simplify the solution for large values of $Pe\frac{D}{x}$.

Aladyev (14) obtained local and average values of heat transfer coefficients for water in turbulent flow in a thermal entrance region. Reynolds modulus varied from 2,500 to 100,000.

Johnson, Hartnett, and Clabaugh (15, 16, 17) investigated the heat transfer coefficient from a mild steel tube to lead-bismuth entectic in laminar, transition, and turbulent flow and to mercury in turbulent flow. All cases were with constant wall heat flux. The test section was a 3/4 in., 18 gage tube four feet long. However, the Nusselt modulus was obtained for eight sections so the results could be applied to the entrance region. In all cases the average Nusselt modulus was considerably below the predictions of the Martinelli-Lyon momentum theory.

Stromquist (18) measured heat transfer coefficients to mercury with constant wall flux. Both fully developed and entrance coefficients were obtained. Tests were also made with sodium additives, which act as wetting agents for mercury and steel. The Nusselt modulus was not appreciably increased with wetting.

Quittenton (19) measured local and average heat transfer coefficients between sodium and a monel tube with constant heat flux. The data were very inconsistent even between runs at identical temperatures and Peclet moduli. When compared with the following theoretical equation of Lyon given in the Liquid-Metals Handbook (20), the measured data were considerably lower and scattered:

$$Nu = 7.0 + 0.025 \, Pe^{0.8} \qquad (3)$$

Harrison (21) made experimental and analytical investigations of the Nusselt modulus for mercury and sodium in an entrance region with constant wall temperature. The heat exchange surface was a copper disk with $\frac{L}{D}$ ratios as low as 1/2. The results with mercury compared quite well with the equation of Poppendick and Palmer (13) for a velocity distribution obeying the 1/7 power law. Sodium data were erratic and below the predicted values. A non-wetting condition was believed to exist which set up an additional thermal resistance at the test section wall.

Berry (22) made an analytical analysis of the Nusselt modulus in an entrance region. An expression was found for the Nusselt modulus as a function of downstream position. The dependence of the entry length on Reynolds modulus and Prandtl modulus is also presented.

Diessler (23) made a comprehensive analytical and experimental study of friction factors and heat transfer coefficients of a fluid with a Prandtl modulus of 0.73 in an entrance region. The theoretical solution for a fluid with a Prandtl modulus of 0.01 in a thermal entrance region with constant heat flux is also given.

Wingo (24) measured the heat transfer coefficient to water in transition flow in an entrance region with constant wall temperature.

Lubarsky and Kaufman (25) reviewed several experimental investigations on the heat transfer coefficient of liquid metals. Both average and entrance region coefficients were discussed. In many cases the data of the original experimentor were re-evaluated using one source for the properties of the fluids involved. Comparisons were made between each work and the appropriate theoretical calculations.

Only two of the experimental works cited, Quittenton (19) and Harrison (21), were concerned with the coefficient for sodium in an entrance region. The results of both were erratic and below theoretically predicted values. An additional thermal resistance caused by non-wetting of sodium and the test section wall could result in erratic coefficients. Moyer and Rieman (26) measured the heat transfer coefficient for sodium and type 347 stainless steel over a temperature range of 100 to 500 degrees centigrade. The measurement was obtained by partially submerging a stainless steel rod in a molten sodium bath. They concluded that wetting had no effect on the heat transfer coefficient. However, in a test section similar to the one used by Harrison (21) with a small diameter, an additional resistance due to wetting could exist which would control the value of the heat transfer coefficient; whereas in a larger, static system the effect could not be noticed.

Objective.--The objective of this thesis is to describe a system for measuring the heat transfer coefficient between liquid sodium and a copper disk in a constant wall temperature entrance region. With the apparatus, the Reynolds modulus and the temperature of the copper-sodium interface could be varied. As the temperature level is increased the degree of wetting is believed to increase. This effect could be observed by comparing measured and theoretically predicted values of the heat transfer coefficient. As the degree of wetting increases the measured results would become more consistent and would approach predicted values.

CHAPTER II

ANALYTICAL SOLUTIONS

Analytical solutions for entrance region phenomena have been developed based on certain postulates. Since experimentally obtained results are to be compared with the theoretical analogy, the assumptions used in the analogy must be adhered to in design of the test apparatus. A summary of analytical derivations along with the assumptions used are presented below.

The mode of heat transfer to a fluid in laminar motion is by molecular conduction. For a fluid in turbulent motion, an additional contribution to heat transfer exists in the eddy motion of fluid particles. However, for liquid metals, the thermal eddy diffusivity is small compared to the thermal molecular diffusivity for low Reynolds moduli. For such a case heat transfer is primarily by molecular conduction. The criterion used by Poppendiek and Palmer (27) for neglecting the contribution of eddy diffusivity to heat transfer is if the mean $\frac{\varepsilon}{\nu}$ ratio is less than 20 per cent of $\frac{\alpha}{\nu}$, or the inverse of the Prandtl modulus.

The heat transfer coefficient is usually expressed in terms of the Nusselt modulus for purposes of derivation and correlation. In terms of this parameter, Equation 2 becomes

$$Nu_x = \frac{h_x D}{k} = \frac{-D \frac{\partial t}{\partial y}(x, 0)}{(t_w - t_m)_x} \tag{4}$$

The terms of Equation 4 are the same as used in Equation 1. The Nusselt modulus defined above is at the position x from the thermal discontinuity. The average Nusselt modulus for length L in the direction of flow is defined as

$$Nu_L = \frac{1}{L}\int_0^L Nu_x dx \tag{5}$$

The general method of solving for the Nusselt modulus is to solve for the temperature distribution within the moving fluid. The Fourier-Poisson equation is used to describe the temperature field due to molecular conduction only in a moving fluid. In cylindrical coordinates it is

$$c\varrho\left[\frac{\partial t}{\partial T} + u_x\frac{\partial t}{\partial x} + u_r\frac{\partial t}{\partial r} + \frac{u_\phi}{r}\frac{\partial t}{\partial r}\right] = \frac{k}{r}\frac{\partial t}{\partial r} + \frac{\partial}{\partial x}\left[k\frac{\partial t}{\partial x}\right] + \frac{\partial}{\partial r}\left[k\frac{\partial t}{\partial r}\right] + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left[k\frac{\partial t}{\partial \phi}\right] \tag{6}$$

The following postulates are made to simplify the equations:

1. Conduction is negligible parallel to the direction of flow; i.e., $k\frac{\partial t}{\partial x} = 0$.

2. The temperature field is symmetrical about the axis; i.e., $\frac{\partial t}{\partial \phi} = 0$.

3. Steady conditions prevail with respect to time; i.e., $\frac{\partial t}{\partial T} = 0$.

4. The velocity distribution is established; i.e., $u_r = u_\phi = 0$.

5. Physical properties are constant and hence independent of temperature; i.e., $\frac{\partial}{\partial x}\left[k\frac{\partial t}{\partial x}\right] = k\frac{\partial^2 t}{\partial x^2}$.

Equation 6 thus reduces to

$$u_x \frac{\partial t}{\partial x} = \alpha \left[\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right] \tag{7}$$

The following boundary conditions for a thermal entrance region are postulated:

1. Initial fluid temperature is uniform; $t(0, r) = t_o$.
2. Wall temperature is uniform; $t(x, b) = t_w$.
3. Temperature field is axially symmetrical; $\frac{\partial t}{\partial r}(x, 0) = 0$.

With the above assumptions and boundary conditions, three solutions for entrance region heat transfer are presented for comparison. They differ only in the postulated velocity distribution. The solutions are as follows:

1. the solution by Graetz (28) for parabolic velocity distribution,
2. the solution by Graetz (28) for uniform velocity distribution,

and

3. the solution by Poppendiek and Palmer (13) for velocity distribution obeying the 1/7 power law.

The solution of Graetz for the average Nusselt modulus of a fluid with parabolic velocity distribution is shown by Harrison (29) to be

$$Nu_L = -1/4 \; Pe \frac{D}{L} \; \ln \left[0.820e^{-2(2.705)^2/Pe\,(D/L)} + 0.0972e^{-2(6.66)^2/Pe\,(D/L)} + 0.0135e^{-2(10.3)^2/Pe(D/L)} + --- \right] \tag{8}$$

Since the solution of Graetz has not been evaluated for the region very near the beginning of a thermal entrance, the following solution by Leveque (30) is used as an asymptote:

$$Nu_L = 1.615 \left[Pe \frac{D}{L} \right]^{1/3} \tag{9}$$

Harrison (31) derives the following equation for the Nusselt modulus of a fluid with uniform velocity distribution based on Graetz's solution:

$$Nu_L = - 1/4 \; Pe \frac{D}{L} \ln 4 \sum_{n=1}^{\infty} \frac{1}{a_n^2} e^{-4a_n^2/Pe \; (D/L)} \tag{10}$$

The velocity distribution of a fluid in turbulent flow can be expressed as the following power law:

$$u = B\left(\frac{y}{b} \right)^m \tag{11}$$

where u is the fluid velocity at a distance y from the wall of radius b and B is a constant. The value of m is shown by Schlichting (32) to depend on the Reynolds modulus. Poppendiek and Palmer (13) have developed the following asymptotic solution for large values of Pe $\frac{D}{x}$ for a fluid obeying the power law velocity distribution:

$$Nu_x = \frac{1}{\Gamma\left(\frac{1}{m+2} + 1\right)} \left[\frac{m+1}{2^{1-m}\,(m+2)} \; Pe \frac{D}{x} \right]^{1/(m+2)} \tag{12}$$

where m is the exponent in the power law. By setting m = 0 Equation 12 can be used as an asymtotic solution to Equation 10

$$Nu_x = 0.564 \left[Pe \frac{D}{x} \right]^{1/2} \tag{13}$$

The average Nusselt modulus then becomes

$$Nu_L = 1.128 \left[Pe \frac{D}{L} \right]^{1/2} \tag{14}$$

At a Reynolds modulus in the range of 100,000, the exponent m is 1/7. Substituting this value into Equation 12, the Nusselt modulus becomes

$$Nu_x = 0.638 \left[Pe \frac{D}{x} \right]^{7/15} \tag{15}$$

The average Nusselt modulus is then

$$Nu_L = 1.196 \left[Pe \frac{D}{L} \right]^{7/15} \tag{16}$$

The solutions for the average Nusselt modulus of the three different velocity distributions are given in Figure 1.

CHAPTER III

DESCRIPTION OF THE APPARATUS

General system.--The conditions used in design and procurement of sodium handling equipment were 600°F. temperature and 30 psig. pressure. The information on materials which will withstand sodium at 600°F. is well summarized in the Liquid-Metals Handbook (33), and this reference was frequently consulted. Clean materials which would not contaminate the sodium were required.

The sodium loop is shown schematically in Figure 2 and by photograph in Figure 3. The apparatus consisted of the following parts: (1) melting tank, (2) filter, (3) sump, (4) pump, (5) test section, and (6) meter.

The melting tank was fabricated from a section of 10 in. black steel pipe. A steel plate was welded to the bottom and tapped for a 1/2 in. pipe outlet. The top of the tank was flanged so sodium bricks could be loaded into the system. On the discharge of the tank, a 1/4 in., 200 lb. stainless steel gate valve was installed so the tank could be isolated from the other parts of the system after the initial melting had been accomplished.

The filter consisted of a porous stainless steel element No. C-14-18, grade E, and a container No. 1000-20 manufactured by Micro Metallic Corporation of Glen Cove, New York. The material was type 304 stainless steel, and connections were 1/4 in. pipe size. A special gasket made from copper plate was used in place of the rubber gasket furnished. A bypass with a 1/4 in., 200 lb. stainless steel globe valve was installed for the filter.

The sump was made from 4 in. schedule 40 type 304 stainless steel pipe. It was 1 ft. - 7 in. long. A stainless steel plate was welded to each end. Three 1/4 in. stainless steel couplings were welded to the sump for sodium and vent lines. All welding was performed by the electric arc method using stainless steel rods.

Two different pumps were tried in the system. The first was an elecgromagnetic type pump. It consisted of the windings of a three phase, 220 volt induction motor and a coil of stainless steel tubing. The copper wires on the armature were removed, and the armature was machined down. A 1/4 in. diameter by 0.01 in. wall, type 304 stainless steel tube was coiled on the armature, and the assembly was replaced in the motor windings. The ends of the tubing were passed through holes in the motor end bells and connected with the other parts of the sodium circuit. The armature was held stationary. The pump contained no moving parts, but was designed to circulate sodium by magnetic flux established by the alternating current in the motor windings. The <u>Liquid-Metals Handbook</u> (34) describes a pump which operates on the same principle. Attempts to circulate sodium with this pump were unsuccessful, and it had to be replaced.

A stainless steel centrifugal pump, type E-1, manufactured by Eastern Industries of New Haven, Connecticut, was then used. The pump was designed for water and similar fluids at low temperatures. To modify it for use with sodium, a new bearing made from high nickel cast iron and a graphite and asbestos packing were installed. Sodium tended to leak through the packing when gas pressure over about 15 psig. was applied to the system. Another disadvantage was the motor operated at too high a temperature due to heat conduction from the pump. A 1/4 in., 200 lb. globe valve was provided on the pump discharge for flow control.

The meter was made from a 2 in. schedule 40 stainless steel nipple 12 in. long. The ends were threaded for two stainless steel pipe caps. A 1/4 in. coupling was welded to the side of the 2 in. pipe near the bottom for a sodium inlet. Another 1/4 in. coupling was welded near the top for a vent. Two electrical probes were placed in the cap at the top of the 2 in. pipe. One probe extended down to just above the sodium inlet; the other was about an inch below the vent. The volume of the meter between probes was 23.05 $in.^3$ The flow rate was measured by closing a valve in the sodium circuit and thus forcing the sodium to flow into the meter. When the sodium came in contact with the long probe an electrical circuit was completed which started a timing device. When contact was made between the sodium and the short probe the timer stopped and an alarm sounded. The valve could then be opened and the meter drained back into the sodium loop. The electrical circuit is shown schematically in Figure 4.

The various parts of the system were connected with 1/2 in. type 304 stainless steel tubing. The fittings used were stainless steel Swagelok compression fittings made by Crawford Fitting Company of Cleveland, Ohio.

In addition to the sodium system, an inert gas and vent system was needed. This consisted of a copper tube joining the vent connection of the meter with the sump, a connection in the tube for gas supply and vent, a cylinder of argon with a pressure regulator, a vacuum pump, two pressure and vacuum gages, and five brass valves. The system was connected so the entire sodium loop could be evacuated or supplied with argon, or either the sump or meter could be vented or subjected to pressure with argon. With this arrangement it was possible to force sodium through the loop into the meter or back out of the meter and thereby verify that the sodium lines were free.

All pieces of equipment containing sodium were heated with electrical heaters fastened to the outside of the equipment. The heaters used were Chromalox, inconel sheathed, of the ring, strip, and tubular design manufactured by Edwin L. Wiegand and Company of Pittsburgh, Pennsylvania. Control was obtained by Variac transformers. The electrical diagram is shown in Figure 5. All heated equipment and tubing were covered with 2 in. thick, premolded Kaylo insulation and Super 48 Insulating Cement.

Test section.--The test section was patterned after the type used by Harrison (21) with some modifications. The necessary features of design were a good approximation to the analytical postulates presented in Chapter II and an adaptation to high temperature sodium. The important restriction was to produce a temperature discontinuity at the test plate. Sodium temperature was to be measured at points just preceding and just following the test section. Between these two points, it was desired to add heat to the sodium only at the copper interface with adiabatic conditions on each side of the copper. Three different designs were tried.

The first test section is shown in Figure 6. It was composed of a 1/8 in. thick copper disk of 3 in. outside diameter and a 1/8 in. drilled hole in the center. A synthetic sapphire gasket was placed on each side of the copper plate to reduce longitudinal conduction of heat. Two identical hydrodynamic calming sections were made to fit against each sapphire gasket. These sections consisted of a carbon steel tube 2 in. long and a 5 in. diameter flange on one end and a 3/4 in. flange on the other. The small flanges were placed against the gaskets. The assembly was held together by bolts through holes in the large flanges. In the initial operation of the apparatus, the assembly slipped out of line and no data were taken.

A second test section was then built and installed. To decrease the possibility of leaks and misalignment, a stainless steel calming tube was silver soldered directly to the flanges and copper test plate. This introduced a larger longitudinal conduction error. The tubing was 1/4 in. outside diameter with a 0.01 in. wall. Bolts were again used between the flanges to increase the strength. The tube was very delicate and evidently became stressed when the test section was installed. No leaks were found during a hydraulic test on the assembly before installation. However, the tube developed a leak when molten sodium was passed through it, and again no data could be taken.

The final test section was similar in design to the second one. The major improvement was an increase in strength with a heavier wall tube. This test section is shown in detail in Figures 7 and 8. The copper test plate was 0.125 in. thick. The outside diameter was 3 in. A 1/16 in. thick by 1.0 in. wide copper flange was soldered around the test plate. A 110 volt 750 watt Chromalox heater was coiled around the flange. A Variac transformer was used to control the heat input. Eight 1/64 in. diameter holes were drilled into the test plate for thermocouple wires. Four holes were drilled in each of two radial lines at 90 degree angles. Thirty gage Leeds and Northrup constantan wires were soldered into these holes. A 30 gage Leeds and Northrup copper wire was soldered to the plate as a common lead to complete the thermocouple circuit. The center of the test section was drilled and reamed to 0.1875 in. This gave an $\frac{L}{D}$ ratio for the heat exchange surface of 0.667. A type 304 stainless steel calming tube was soldered to each side of the copper plate and to a flange. The tubes were 0.2535 in. outside diameter and drilled and reamed to the same inside diameter as the copper plate. The tubes and plate were assembled on a drill rod and silver soldered together. The tube on the upstream side was 3-1/4 in. long, giving a hydrodynamic calming $\frac{L}{D}$ ratio of 17.3. The tube on the downstream side was 1-3/4 in. long. Four 1/4 in. diameter bolts between the two flanges increased the strength.

The heat flux and copper-sodium interface temperature could be obtained from the temperature measurements made at each of the radial positions in the copper plate. The following equation can be used:

$$q = \frac{2\pi kL\ (t - t_w)}{\ln \frac{r}{b}} \qquad (17)$$

A graphical procedure is suggested by rearranging Equation 17 to

$$t = t_w + \frac{q}{2\pi kL} \ln \frac{r}{b} \qquad (18)$$

Then by plotting the temperature at a given radius versus the logarithm of the ratio of that radius to the radius of the wall, a linear relationship is obtained with a slope of $\frac{q}{2\pi kL}$ and intercept of t_w. The average heat transfer coefficient for the length L can be calculated from

$$h_L = \frac{q}{A(t_w - t_m)} \tag{19}$$

where q and t_w are found as outlined above, A is the area of the interface, and t_m is the average of sodium temperature measurements in and out of the test section. The method given for finding the heat flux and wall temperature are based on the assumption that heat flow in the copper plate is in the radial direction only. The surfaces of the copper plate were covered with insulation except at the center where the tubes were connected to the plate. Therefore, heat loss from the plate will be negligible except for longitudinal conduction in the tubes. A method for calculating the conduction error in the calming tubes is given in Appendix C.

The effect of longitudinal conduction within the moving fluid on entrance region heat transfer was examined by Harrison (35). He concluded that heat conduction within the fluid was negligible if the Peclet modulus is greater than 400. The Peclet modulus is the product of Reynolds and Prandtl moduli. The Prandtl modulus of liquid sodium is approximately 0.01. The corresponding Reynolds modulus for a Peclet modulus of 400 is 40,000. Thus for Reynolds moduli of 40,000 or greater, the effect of conduction within the sodium is negligible. The system as designed could be used over a range of Reynolds modulus of

40,000 to 100,000 and hence would be operating above the minimum Reynolds modulus for a conduction error in the sodium.

Instrumentation.--The instrumentation consisted of metering and temperature indicating systems. The metering apparatus is described above. In addition to the eight temperature measurements on the test plate, two additional temperatures were required to compute the heat transfer coefficient. These were the sodium temperatures at the inlet and outlet of the test section. The thermocouples used were 20 gage Leeds and Northrup chromel-alumel. The hot junction was placed in the sodium stream through a thermocouple packing gland. A lava disk was used in the gland to prevent leaks. The glands were fitted into 1/4 in. stainless steel tees. The two tees were connected to the flanges on each side of the test section by close pipe nipples. Additional chromel-alumel thermocouples were placed at random on the outside of equipment and tubing so temperatures throughout the system could be obtained. This proved extremely helpful during heating and operation of the equipment. It was found that the short lengths of tubing on each side of the copper plate in the test section required heating during warmup of the system. A heater was made from 22 gage nichrome resistance wire with fiberglass insulation and coiled on the tubes. A chromel-alumel thermocouple was located 1-5/8 in. upstream from the copper plate on the outside of the calming tube so the temperature there could be maintained above the freezing point of sodium during the warmup period. The two groups of chromel-alumel and copper-constantan thermocouples were each brought to a terminal block. An eleven position Leeds and Northrup switch was used for each group of thermocouples. From each switch a single cold junction was maintained at 32°F. in an ice bath and placed in series with a No. 8662 Leeds and Northrup Portable Precision Potentiometer. With this arrangement the temperature at each thermocouple position could be quickly obtained by turning the switch to the appropriate position and reading the millivolts indicated on the potentiometer.

CHAPTER IV

PROCEDURE

Since the arrangement of the equipment did not permit complete drainage, sections of the system were individually flushed with trichloroethylene during construction. This removed oil and grease and left the inner surfaces of the equipment free from any impurities which might contaminate the sodium.

After the apparatus had been assembled, it was carefully tested for leaks. For this purpose, a portable air compressor was temporarily connected to the system. The pressure was brought up to approximately 30 psig., and leaks were located by brushing soap solution on all joints. Considerable difficulty was encountered in attempting to get the system completely air tight. Particular trouble was noted with the threaded stainless steel joints and in the compression fittings used on the copper gas line. Many joints were sealed by silver soldering. Leaks through the valve stem packings were also quite frequent.

Construction was completed by providing heaters and insulation for all equipment and flow passages which were to contain sodium. All remaining traces of trichloroethylene were removed by heating the apparatus. Air and vapors were removed from the system by a vacuum pump. The system was then filled with argon, which is completely inert to sodium. The original intention was to keep a slight positive pressure of argon on the system at all times to prevent infiltration of air. However, during the period of modifications which were found necessary for the pump and test section, a positive pressure was not always maintained.

Protective clothing consisting of gloves, goggles, aprons, and helmets were worn during handling of solid sodium and operating the apparatus. As a further precautionary measure, two fifty-pound containers of Ansul Met-L-X Dry Powder were purchased for use as a fire extinguisher in the event of a molten sodium fire.

Five two-pound bricks of metallic sodium manufactured by National Distillers Chemical Company of Ashtabula, Ohio, were placed in the loading tank. The sodium had been stored in sealed metal cans containing an inert atmosphere. However, the bricks were covered with a thin film of oxide. No attempt was made to remove the oxide before loading. The top of the loading tank was then bolted in place, and again the system was evacuated and filled with argon. The discharge valve on the loading tank was closed. The loading tank as well as all other parts of the system were heated to slightly above the melting point of sodium, 208°F. The pressure, which had increased during heating, was equalized on both sides of the discharge valve. The valve was then opened and the system filled with sodium. The loading tank was isolated from the other components, after it had been emptied, by closing the valve. The tank was then opened; and it was observed that most of the pure sodium had flowed out, leaving a heavy deposit of sodium oxide. Sodium oxide is very insoluble in liquid sodium at low temperatures[3] and is also lighter than sodium. Hence, when the sodium melted, the oxides formed a layer of solids which remained in the tank. The porous stainless

[3]See reference 36 for the solubility of sodium oxide.

steel filter, located on the discharge of the loading tank, effectively removed any particles of insoluble sodium oxide remaining in the molten sodium.

Attempts were then made to circulate the sodium with the electromagnetic pump. It was found necessary to wrap a heater around the two tubes on each side of the copper plate in the test section. Considerable difficulty was also experienced in heating the stainless steel coil in the pump above 208°F. The voltage was increased on the motor windings until a mercury-in-glass thermometer placed against the coil of tubing indicated a temperature above the melting point of sodium. Sodium could then be forced through the pump and test section by increasing the pressure on the sump with argon. However, the pump would not circulate the sodium. Since the motor was three phase, the possibility existed of wiring it so the magnetic flux was opposite to the direction of the helical coil. This possibility was eliminated by interchanging two of the wires, which reverses the direction of rotation of a three phase motor. The pump still failed to work. Reasons for the pump failure were not determined; although one limitation which may have affected its operation was noted. The voltage which could be applied was severely restricted by the low temperature insulation on the motor windings.

A small centrifugal pump was then installed in place of the electromagnetic pump. The apparatus was again heated and another attempt made to pump sodium. This time sodium could not be forced through the test section. It was then discovered that a small amount of sodium had leaked between the sapphire gasket and copper plate. The test section had then slipped out of alignment so there was not a complete passage through which the sodium could flow.

The test section was then replaced by a second model. A leak developed when the pressure in the sump was increased to circulate the sodium; therefore, a third test section had to be installed.

The system was again heated and the pressure on the sump increased. Although the pressure was raised as high as 20 psig. in addition to approximately 17 psig. developed by the pump, it was still impossible to circulate the sodium. It was found that air had entered the apparatus during modifications of the pump and test section. When these components were removed, precautions were taken to eliminate air by either capping the lines or replacing the section with tubing. When each new item was installed, it was filled with argon immediately before installation. However, the precautions were evidently not rigorous enough.

The equipment was then dismantled and visually inspected. Heavy concentrations of sodium oxide were found in the pump, test section, and adjacent tubing which had been replaced during modification. Some deposits of sodium oxide were also found in the sump, and small traces were noted around some of the fittings where air had evidently leaked in. Sodium oxide can be identified and distinguished from pure sodium by its appearance. Pure sodium has a bright, silvery color while sodium oxide is dull grey.

The sodium was removed from all components by first submerging them in a tank of hot oil. The temperature of the oil was maintained above the melting point of sodium. As the sodium melted it flowed from the equipment and settled to the bottom of the tank. Sodium does not react with oil below the cracking temperature, and it was protected from reaction with the atmosphere by the oil bath. The remaining sodium and sodium oxide were removed by reacting them with methyl alcohol. This reaction is vigorous but not rapid enough to be dangerous. Precautions must be taken as the reaction liberates hydrogen gas. Any final particles of sodium were removed by a solution of 20 per cent water and 80 per cent methyl alcohol. This reaction can be dangerous if there are large particles of sodium remaining or if the alcohol and water are added separately. The final steps in cleaning were to flush the components with water and then with trichloroethylene to remove oil. A visual examination of the inner surfaces showed no corrosion or damage from sodium on any of the equipment, including the porous stainless steel filter element. The sodium had remained in the apparatus a period of approximately eight weeks. For the major portion of that time the system had remained cold; however, it had undergone about ten heating and cooling cycles, each one day in duration.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--As a result of the construction and operation of the apparatus the following conclusions are made:

1. The final test section fabricated for the present apparatus could be used for the experimental measurement of liquid sodium in a thermal entrance region. The deviation from the assumptions of the theoretical analogy is considerable. However, the design is a compromise between a more exact representation of the theoretical case and a practical model which would operate satisfactorily.

2. The type of electromagnetic pump used is a feasible method of circulating sodium but requires further development to produce a satisfactory design.

3. The method used to load sodium into the apparatus and to filter the oxides and impurities was very satisfactory. The porous stainless steel filter was effective and readily adapatable to liquid sodium.

4. The tubing and fittings were assembled with little difficulty and were well suited to laboratory scale handling of liquid sodium. The standard stainless steel valves with asbestos packing were unsatisfactory for use with sodium because of leaks at the valve stems.

5. A small amount of silver solder was used to seal some joints and to assemble the test section. Silver is soluble in sodium and this method of welding is not normally recommended. However, on equipment

designed for very limited contact time with sodium, silver solder could be used. It is a very convenient method of welding delicate parts and was employed for this reason.

6. The method of removing sodium from equipment was satisfactory. Had it been possible to drain all the apparatus without dismantling it, the cleaning operation would have been considerably simplified.

Recommendations.--A slightly modified system is recommended to be constructed employing a similar test section to the final model discussed above. The problem of pumping liquid sodium is indeed difficult. A variety of electromagnetic as well as centrifugal type pumps have been developed for use with liquid metals. The cost of these pumps is quite high and usually eliminates them from consideration for small scale experimental work. The centrifugal pump used in the present system was not sufficiently tested to draw a definite conclusion on its use with sodium. The pump is believed to have a limited operating period because of the excessive motor temperature and the small leak along the shaft. A gear pump, with a safety relief, or a sump pump may possibly be used. Provisions should be made so the motor will not be heated excessively by conduction from the pump. A system could feasibly be constructed in which sodium could be circulated by gas pressure and thus eliminate the pump. Two large reservoirs would be needed. This method has the disadvantage that all measurements for each run must be made while one reservoir is being emptied and the other filled. The length of the run is dependent on the amount of sodium used. If a pump can be used it is an improvement because data can then be taken at leisure and the flow rate is steady. A test loop could be constructed employing both the reservoirs and the pump. The pump should be provided with valves and a bypass so data could be taken if it failed to operate.

In the design of liquid metal apparatus, provisions for complete drainage should be carefully considered. This would greatly simplify precleaning operations as well as the removal of the liquid metal after tests were completed.

Extreme care should be taken to prevent contamination of sodium. It is important that all leaks be completely eliminated. Molten sodium leakage from equipment is a dangerous hazard, and infiltration of air forms sodium oxide which may be deposited on surfaces or cause plugging of flow passages. Care should be taken in replacing or repairing parts of the system. A section can easily be removed if the temperature is below the melting point of sodium. The exposed ends should be capped immediately. When a new section is installed it should be thoroughly cleaned before installation. A connection to the section should be made so all air can be evacuated and replaced by argon after the section is in place. Adequate precautions with liquid sodium systems are imperative for successful tests.

APPENDIX

APPENDIX A

NOMENCLATURE

<u>Latin Letter Symbols</u>

A	area, ft.^{2}
a_n^1	positive roots of $J_0(a)$
B	constant
b	radius or half distance between plates, ft.
C	circumference, ft.
c	heat capacity, BTU/lb.-°F.
D	diameter, ft.
h	heat transfer coefficient, BTU/hr.-ft.^{2}-°F.
k	thermal conductivity, BTU/hr.-ft.-°F.
L	length of flow passage, ft.
M	constant
m	exponent in power law expression
N	constant
n	see Appendix C
q	heat transfer rate, BTU/hr.
r	radius, ft.
T	time, hr.
t	temperature, °F.
u	velocity, ft./sec.
V	average fluid velocity, ft./sec.
W	flow rate, lb./hr.

x, y	distance coordinates, ft.

<u>Greek Letter Symbols</u>

α	thermal diffusivity, ft.^{2}/hr.
Γ	gamma function
Δ	an increment
ϵ	eddy diffusivity, ft.^{2}/hr.
θ	see Appendix C
μ	dynamic viscosity, lb./ft.-sec.
ν	kinematic viscosity, ft.^{2}/hr.
ρ	density, lb/ft.^{3}
ϕ	angular displacement

<u>Subscripts</u>

c	convective heat transfer
L	average value over length L
m	mean fluid property
0	initial condition
r	condition at radius r
w	condition at the wall
x	local value

<u>Dimensionless Moduli</u>

Nu	Nusselt, hD/K
Pe	Peclet, DV/α
Pr	Prandtl, $C\mu/K$
Re	Reynolds, $\rho VD/\mu$

APPENDIX B

FIGURES

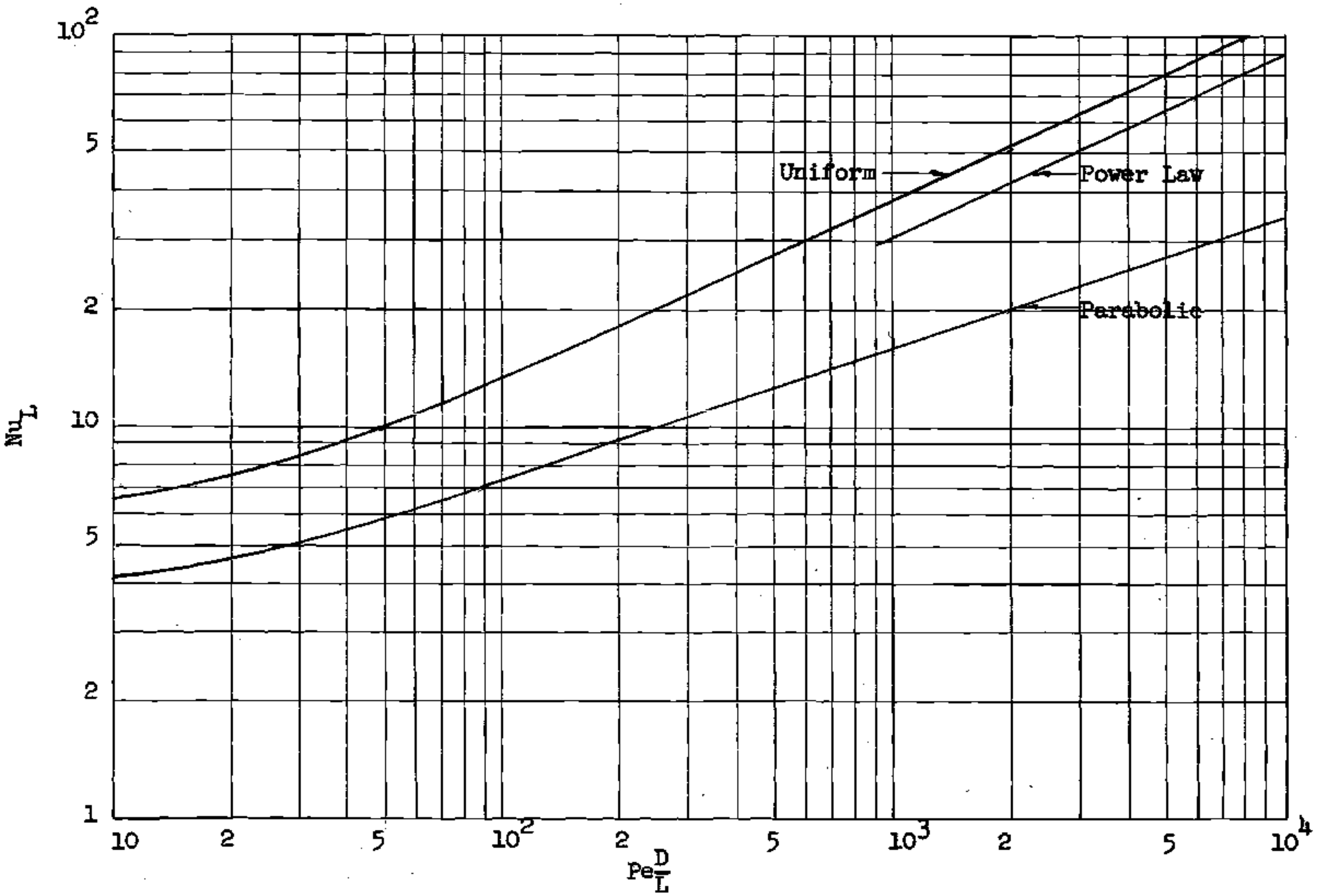

Figure 1. Average Nusselt Moduli in a Thermal Entrance Region of Constant Wall Temperature

KEY TO FIGURE 2

A	Loading Tank
B	Filter
C	Sump
D	Pump
E	Test Section
F	Meter
G	Gate Valves
H	Glove Valves
	Sodium Lines
	Gas Lines

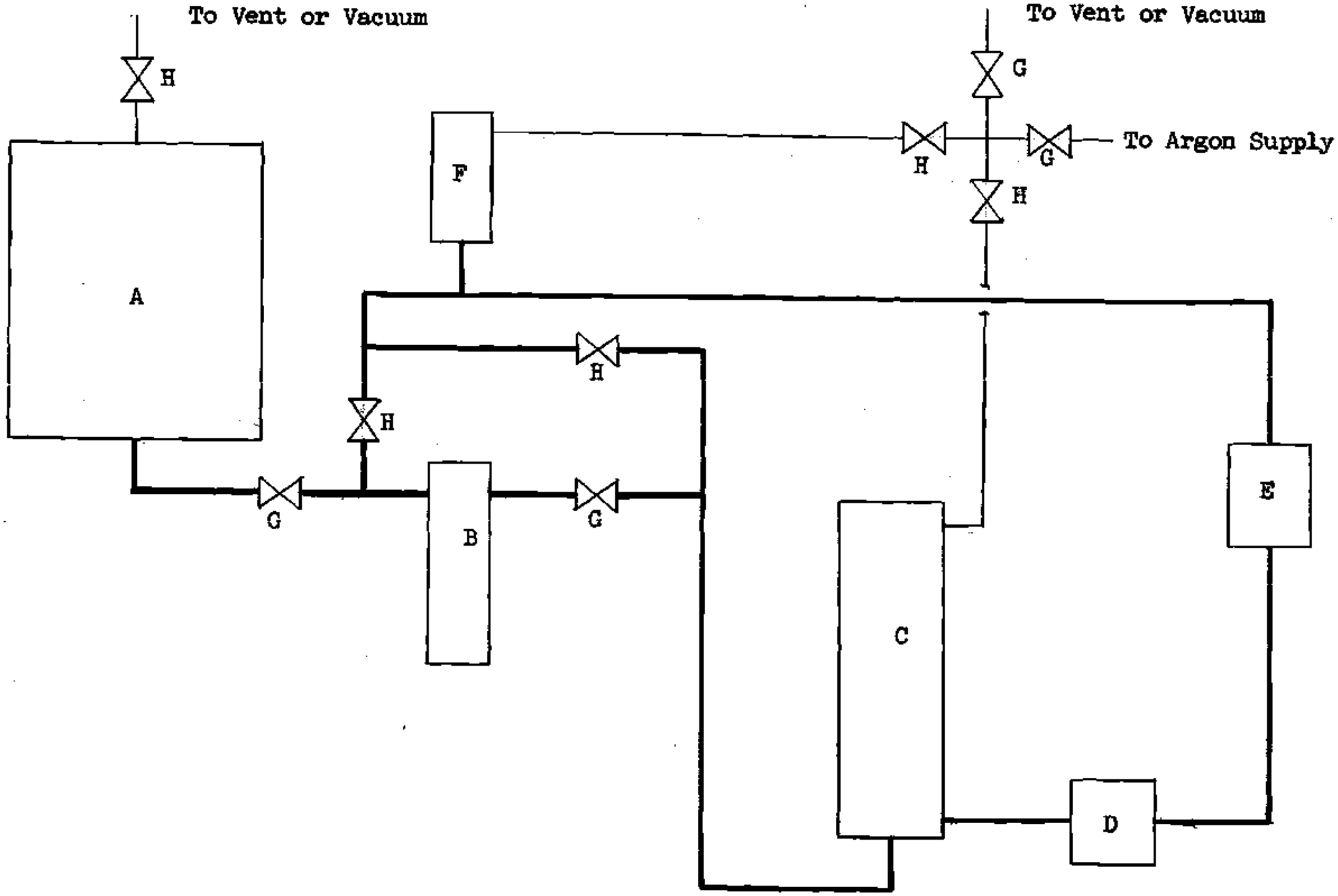

Figure 2. Schematic Diagram of Apparatus

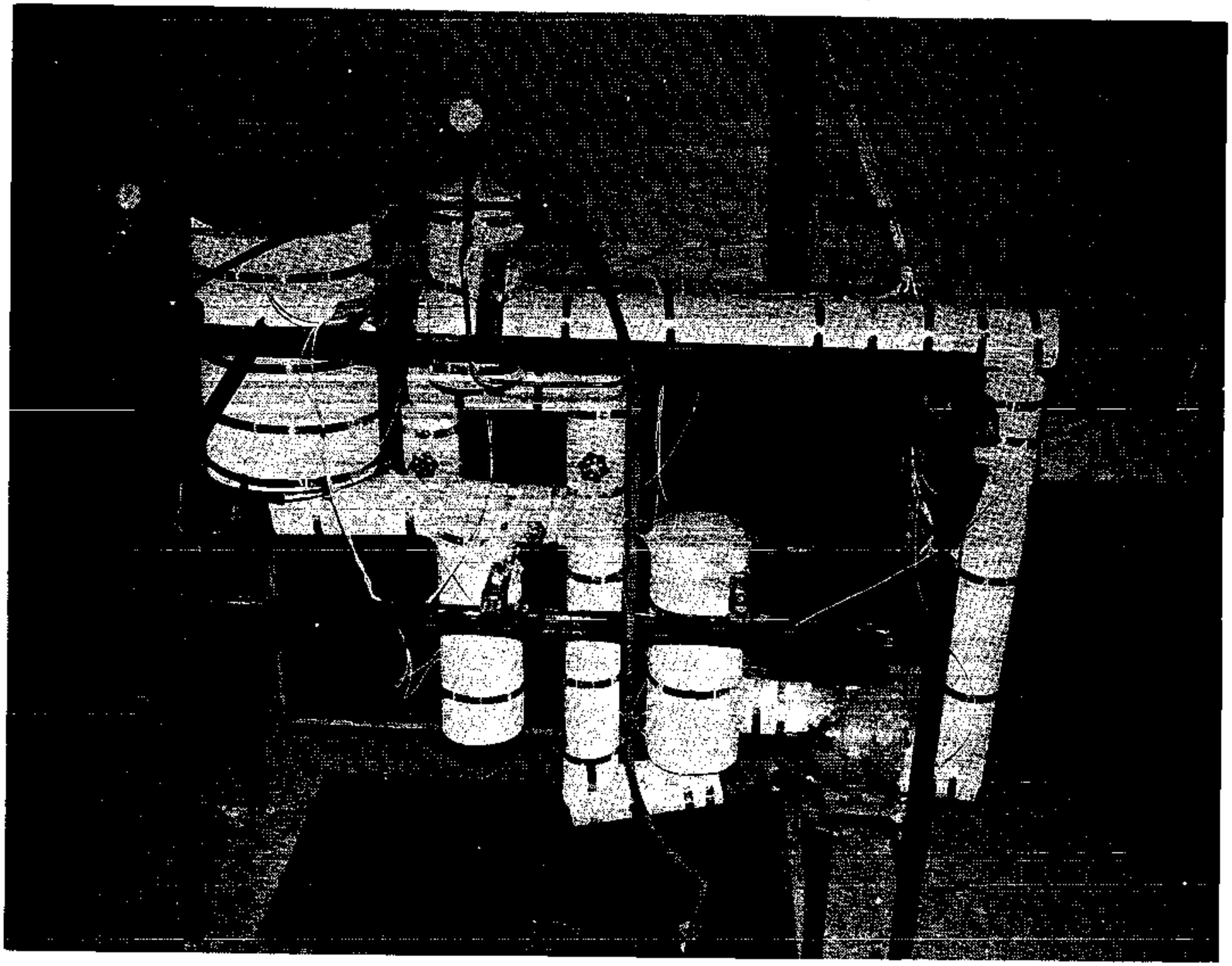

Figure 3. Photograph of Apparatus.

KEY TO FIGURE 4

A	Isolation Transformer
B	NE-51 Power Pilot Light
C	Red 6 Volt Pilot Light for High Level
D	Alarm for High Level
E	Double Pole Double Throw 110 Volt A.C. Latching Relay
F	Green 6 Volt Pilot Light for Low Level
G	Timer
H	Amber 6 Volt Pilot Light for Timer Reset
J	Single Pole Double Throw 110 Volt A.C. Relay
K	Four Connector Male Plug
L	Receptacle
M	Meter
	Fuse
	Timer Reset

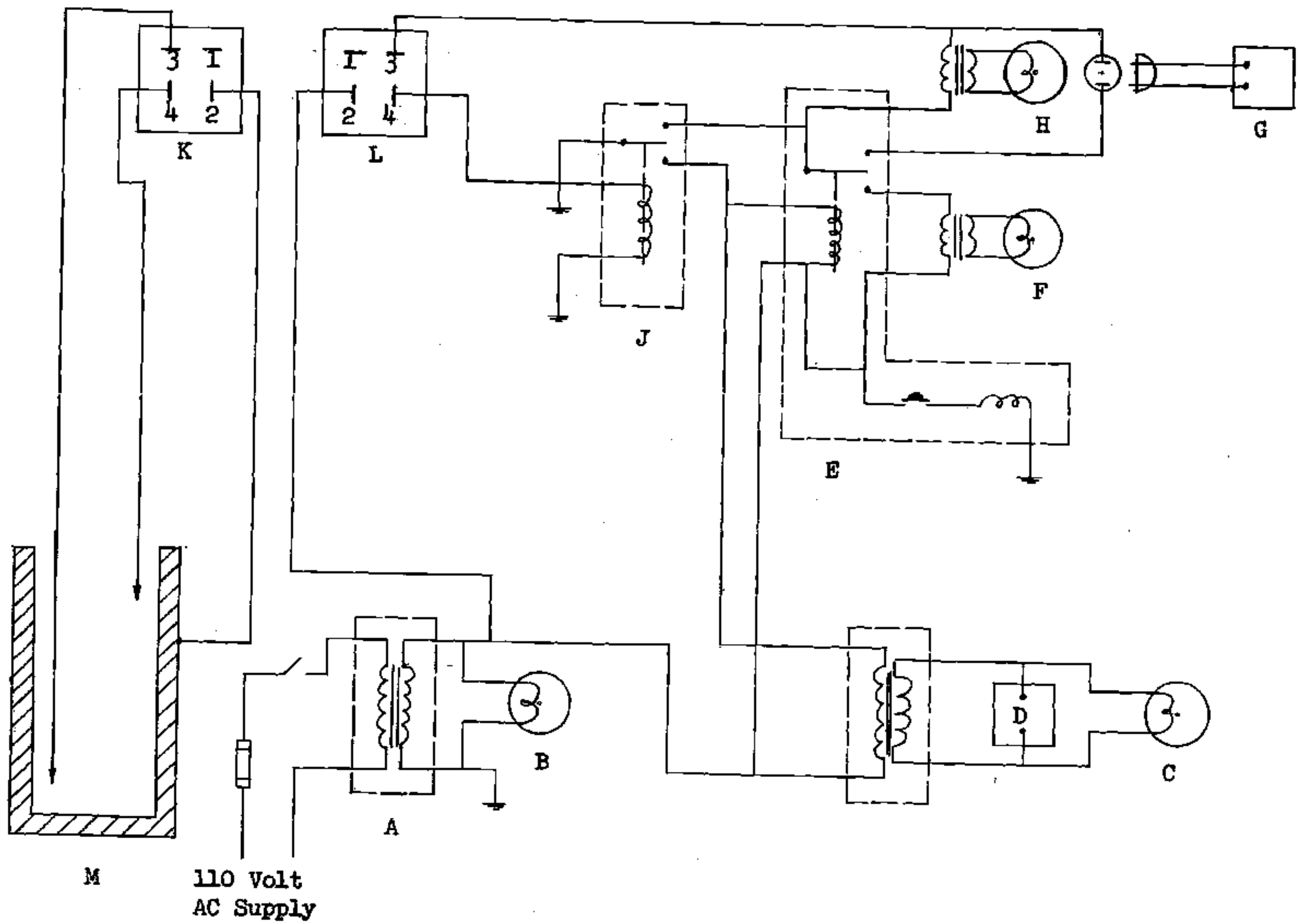

Figure 4. Schematic Diagram of Timing Circuit

KEY TO FIGURE 5

A	Loading Tank Heaters
B	Filter Heater
C	Sump Heaters
E	Test Plate Heater
F	Meter Heater
G	Tubing Heaters
H	Resistance Wire Heater at Test Section
	Variac Transformer
$\boxed{750}$	Resistance Type Electrical Heater with Wattage Rating
$\boxed{00}$	Convenience Outlet
	Fuse

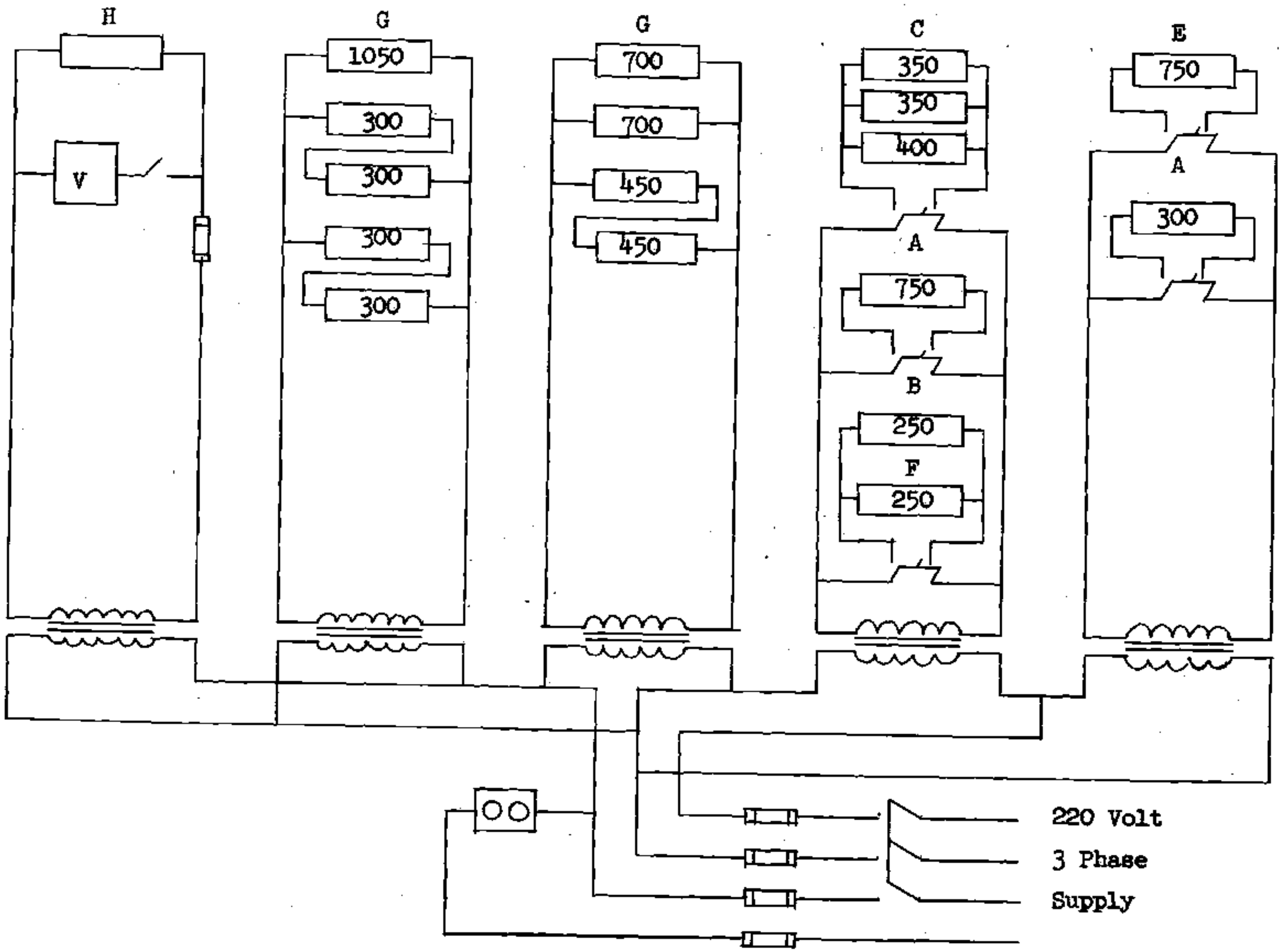

Figure 5. Schematic Diagram of Heating Circuit

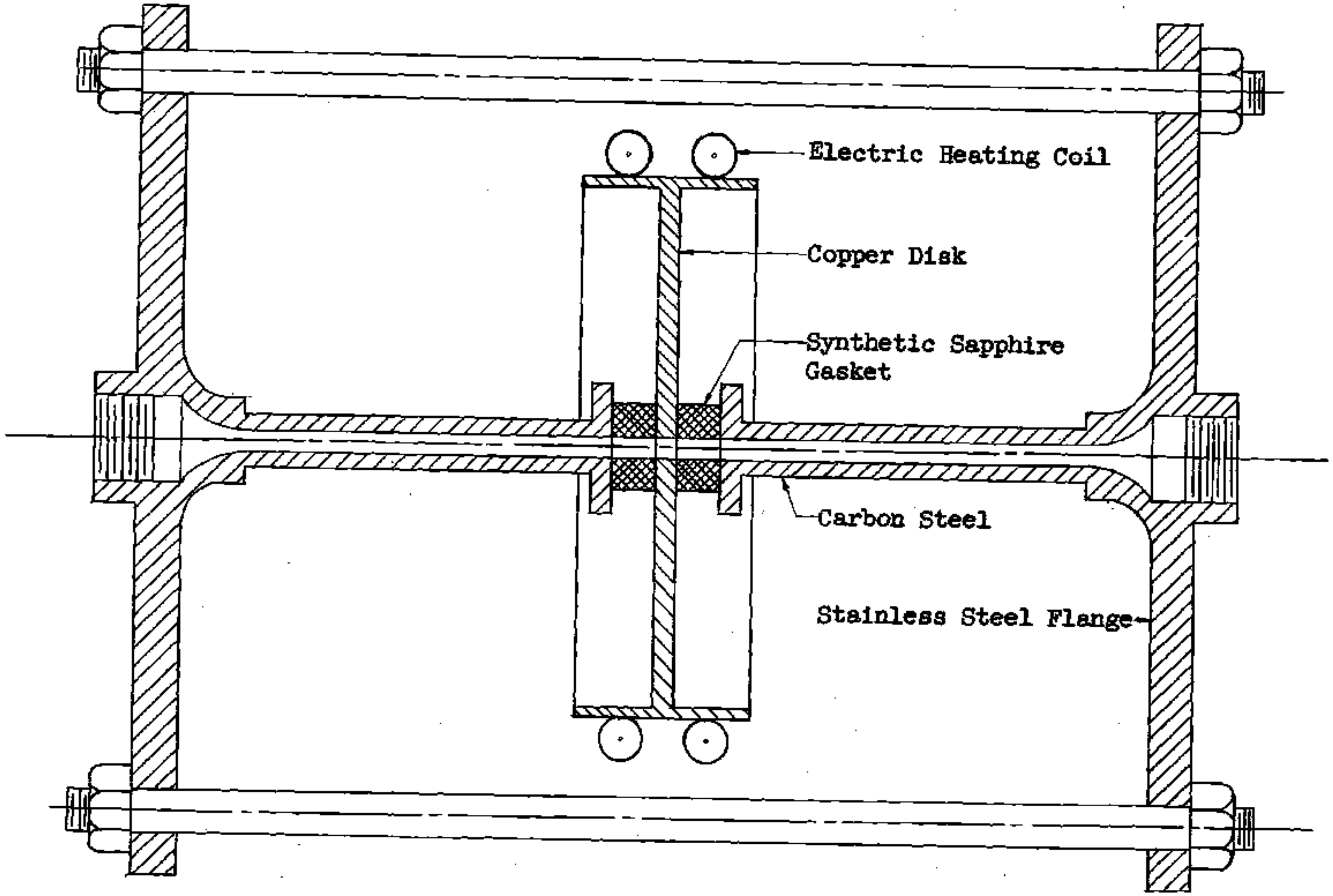

Figure 6. Sketch of Initial Test Section

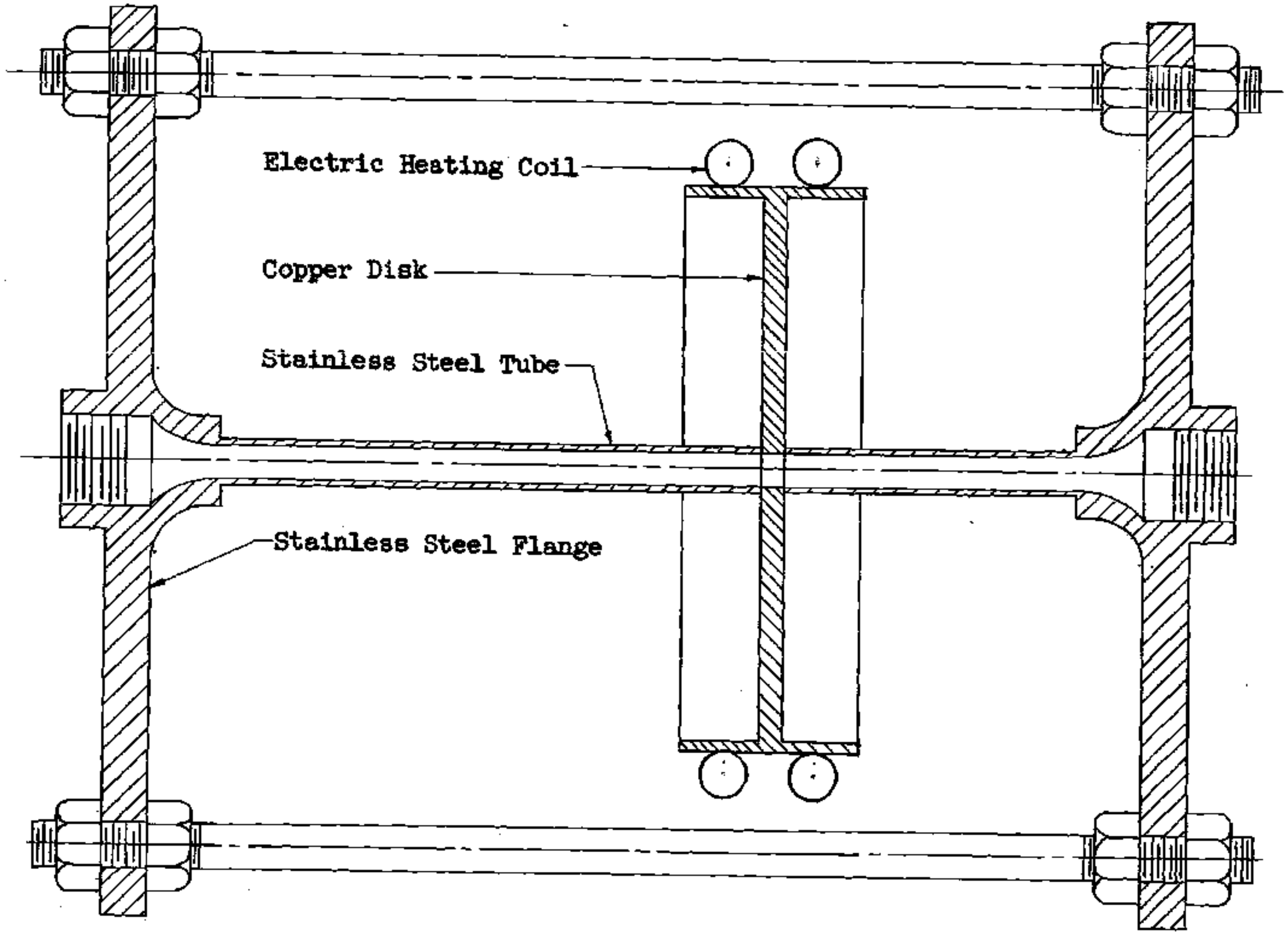

Figure 7. Sketch of Final Test Section

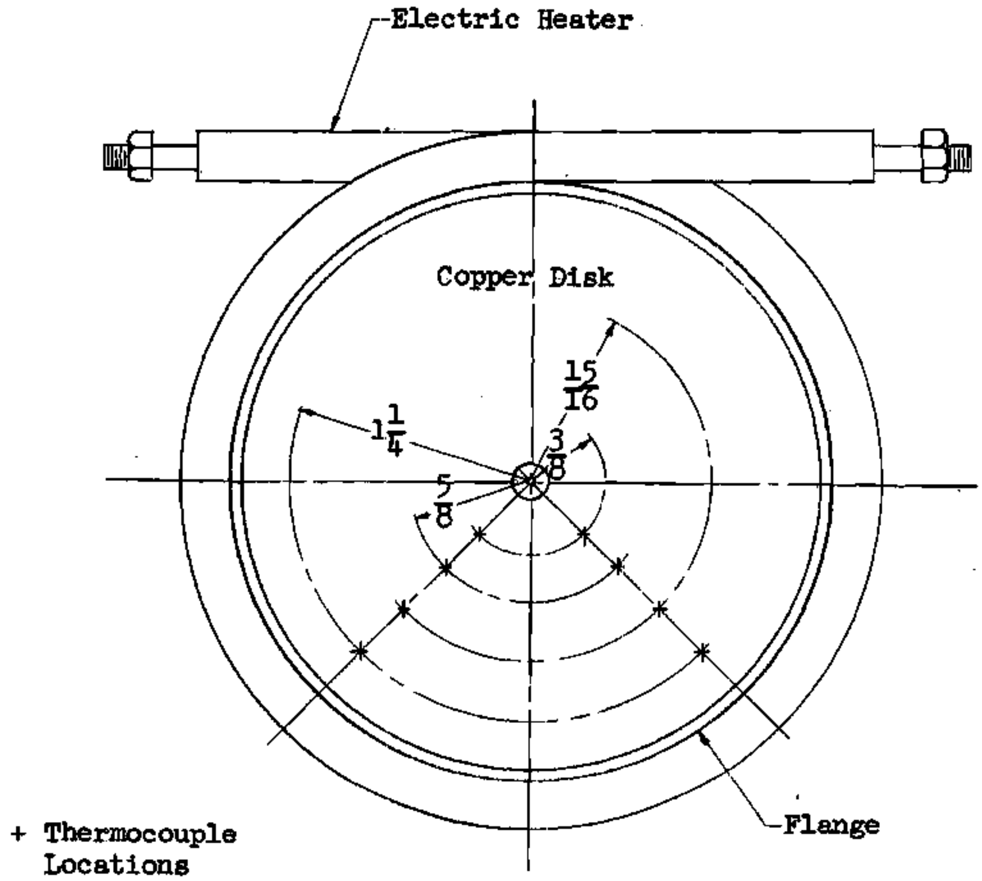

Figure 8. Sketch of Heat Exchanger

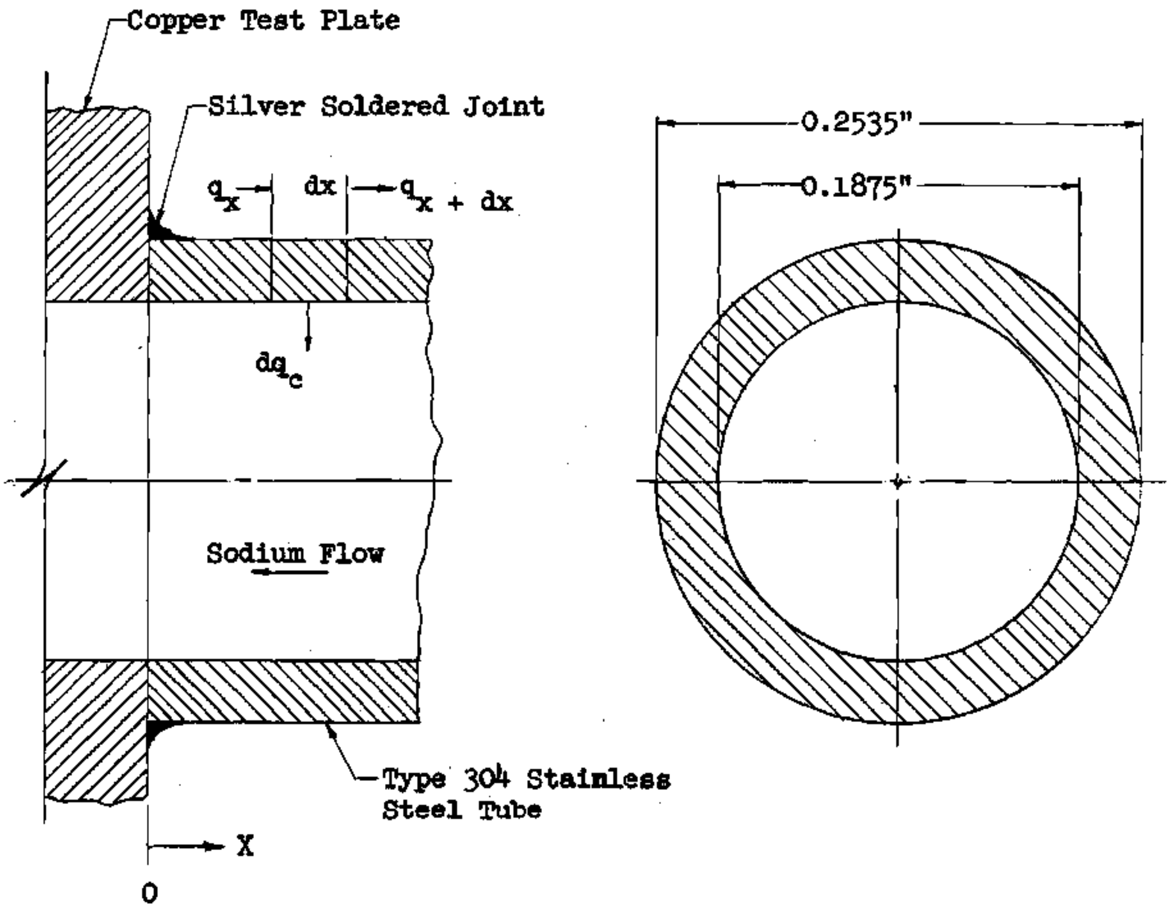

Figure 9. Detailed Sketch for Use in Examination of Longitudinal Conduction

APPENDIX C

EXAMINATION OF LONGITUDINAL HEAT CONDUCTION

A method is presented here to account for the longitudinal heat conduction from the test plate. The analysis has been considerably simplified so that a closed mathematical rather than a numerical solution may be obtained. The method is then used to evaluate the heat loss for a hypothetical case.

The following assumptions are employed:

1. There is no radial temperature gradient in the stainless steel tube.
2. The heat loss to environment is negligible.
3. The thermal conductivity of the tube is constant.
4. The temperature of sodium is constant.
5. The heat transfer coefficient to sodium is constant.
6. The contribution to heat conduction of the silver solder fillet is negligible.

The symbols used in the analysis are as follows:

1. A = cross sectional area of tube, ft.^{2},
2. C = circumference of tube, ft.,
3. t_o = temperature of copper-sodium interface, °F.,
   = temperature of tube at $x = 0$,
4. t = temperature of tube at any point x, °F.,
5. t_m = mean temperature of sodium, °F.,
6. $\theta = t - t_m$, F.,

7. k = thermal conductivity of tube, BTU/hr.-ft.-F., and

8. h = heat transfer coefficient of sodium, BTU/hr.-ft.^{2}-F.

The heat flux at a point x can be expressed as

$$q_x = -kA\frac{dt}{dx}$$

The heat flux at a differential increment from the point x is

$$q_{x\,+\,dx} = -k\ A\ \frac{d}{dx}\left(t + \frac{dt}{dx}\,dx\right)$$

The rate of heat transfer to sodium is given by

$$dq_c = h\ C\ (t - t_m)\ dx$$

For steady state conditions a heat balance on the element dx gives

$$q_x = q_{x\,+\,dx} + dq_c$$

then

$$k\ A\ \frac{d^2t}{dx^2} = h\ C\ (t - t_m)$$

or

$$k\ A\ \frac{d^2\theta}{dx^2} = hC\theta$$

let

$$n = \sqrt{\frac{hC}{kA}}$$

the equation becomes

$$\frac{d^2\theta}{dx^2} = n^2\theta$$

since n is considered constant

$$\theta = Me^{-nx} + Ne^{nx}$$

To evaluate a particular case for the magnitude of the heat conduction in the tubing, the following conditions are assumed:

1. $t_m = 392°F.$,
2. $t_o = 600°F.$,
3. Re = 50000,
4. k = 14.8 BTU/hr.-ft-F., and
5. h is given by Equation 3[4]

$$\frac{hD}{k} = 7 + 0.025\ Pe^{0.8} \tag{3}$$

The properties of sodium at 392°F. or 200°C. listed in the Liquid-Metals Handbook (37) are

1. density = 56.4 lb./ft.^{3},
2. viscosity = 3.02×10^{-4} lb./ft.-sec.,
3. thermal conductivity = 47.1 BTU/hr.-ft. F., and
4. heat capacity = 0.320 BTU/lb.- F.

The Prandtl modulus becomes

$$Pr = \frac{c\mu}{k} = 0.00739$$

The Peclet modulus is

$$Pe = (Pr)(Re) = 370$$

[4]Equation 3 is applicable for uniform heat flux far removed from an entrance region. The assumption that the heat transfer coefficient is constant and represented by this equation may introduce an error but permits considerable simplification.

The heat transfer coefficient is calculated to be

$$h = \frac{47.1 \times 10^{-2}}{1.562} \left[7 + 0.025(370)^{0.8} \right]$$

$$h = 29600 \text{ BTU/hr. - ft.}^2\text{-F.}$$

The constant n can now be calculated as

$$n = \sqrt{\frac{hC}{kA}}$$

$$n = \sqrt{\frac{(29,600)(0.1875)(12)(4)}{(14.8)(0.0290)}}$$

$$n = 790$$

The boundary conditions are

1. $\theta_o = 208°F.$ and
2. $\left.\frac{d\theta}{dx}\right]_L = 0$

where L shall be taken as 3.25 in., which is the distance to the tube inlet.

The constants of integration can be found as

$$208 = Me^{-0} + Ne^{0}$$

or

$$208 = M + N$$

$$\left.\frac{d\theta}{dx}\right]_L = -nMe^{-nL} + nNe^{+nL}$$

solving the two equations for N

$$N = 208 \left(\frac{1}{e^{2nL}+1}\right)$$

For L = 3.25 in. the value of N is approximately zero.

Therefore

$$\theta = 208e^{-790x}$$

The heat loss from the tube may now be evaluated.

$$dq_c = hC\theta dx$$

$$dq_c = 208hCe^{-790x}dx$$

$$q_c = \frac{-208hC}{790}e^{-789x}\Big]_0^L$$

$$q_c = \frac{208hC}{790}$$

q_c = 382 BTU/hr.

The theoretical heat transfer rate for the copper test plate with no longitudinal conduction can be found from extrapolation of the power law curve on Figure 1.

$$Pe\frac{D}{L} = 370\left(\frac{1}{0.667}\right)$$

$$Pe\frac{D}{L} = 555$$

which gives

$$Nu_L = 23$$

$$\frac{hD}{k} = 23$$

h = 69,400 BTU/hr.-ft.^{2}-°F.

$$q = hCL\theta$$

$$q = \frac{(69400)(\pi)(0.1875)(0.125)(208)}{144}$$

q = 7380 BTU/hr.

The increase in temperature of the sodium can now be calculated.

$$Re = \frac{4W}{\mu\pi D}$$

$$W = \frac{(50000)(3.02)(10^{-4})(3600)(\pi)(0.1875)}{(4)(12)}$$

$$W = 666 \text{ lb./hr.}$$

$$q = Wc\,\Delta t$$

solving for the sodium temperature change, Δt,

$$\Delta t = \frac{q}{Wc}$$

$$\Delta t = \frac{7380}{(666)(0.320)}$$

$$\Delta t = 35.2 \text{ F.}$$

Since the temperature rise is appreciable, the heat transfer rate must be modified using an average sodium temperature. Assuming an approximate temperature rise of 32 F, the new calculation gives

$$q = \frac{(69400)(\pi)(0.1875)(0.125)(192)}{144}$$

$$q = 6800 \text{ BTU/hr.}$$

The heat loss due to conduction in the stainless steel tube downstream of the test section will be

$$q_c = \frac{hC\theta}{n}$$

$$q_c = \frac{(29600)(0.1875)(176)\pi}{(790)(12)}$$

$$q_c = 324 \text{ BTU/hr.}$$

The per cent error shall be defined as the total heat loss by conduction in the tubes to the theoretical heat transfer rate. It is therefore

$$\text{error} = \frac{\text{total } q_c}{q}(100)$$

$$\text{error} = \frac{382 + 324}{6800}(100)$$

$$\text{error} = 10.4 \text{ per cent}$$

The deviation from the case of a temperature discontinuity at the inlet and outlet of the test surface is thus appreciable. However, the extremely high exponent in the equation of temperature difference versus the longitudinal direction indicates a steep temperature gradient can be expected near the position $x = 0$.

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