HEAT TRANSFER COEFFICIENTS FOR CONDENSATION OF LIQUID METAL VAPORS INSIDE A VERTICAL TUBE

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1960

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Date thesis is presented July 3, 1959

Typed by Patricia Malango

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. J. G. Knudsen who guided the author in this project.

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INTRODUCTION

Liquid metal technology is becoming an increasingly important branch of engineering science and practice. High thermal conductivities and desirable fluid properties coupled with low vapor pressures, make liquid metals an ideal heat transfer medium at high temperatures. One of the first applications of liquid metals was the use of sodium as a static valve coolant in aircraft engines. Today various liquid metals find use in many phases of industry. Of particular importance is the use of liquid metals as a nuclear reactor coolant, and, in some cases, as a combination coolant and fuel carrier.

Natural and forced convection heat transfer with liquid metals has been studied extensively (8). Boiling heat transfer has been studied by Lyon, Foust, and Katz (10 and 5, p. 85-55). The systems most frequently studied are mercury, sodium, potassium, sodium-potassium mixtures, cadmium, and the lead-bismuth eutectic. Very little experimental data exists for heat transfer by condensation of metal vapors (12, p. 7-21). As materials of construction become more reliable, higher temperatures will be reached and the importance of condensing heat transfer will grow.

The Nusselt relationship, equation (1), has been used sucessfully for predicting condensing coefficients for filmwise condensation of non-metalic vapors. The condensing coefficients which have been obtained experimentally on liquid metal vapors are much lower than those predicted by the Nusselt equation. This investigation was initiated to obtain more information on the condensation of liquid metal vapors.

The work included a study of mercury, mercury with 0.3% sodium, mercury with 1.0% sodium, and cadmium. Water was used to determine if the apparatus operated correctly. The condensing coefficients obtained for the mercury were in accordance with the values obtained by Misra and Bonilla (12, p. 17) on an air cooled condenser. The heat transfer coefficients obtained for the sodium-mercury amalgams were no different than the pure mercury coefficients. This would indicate that the sodium at the normal boiling point of mercury (675°F) is not volatile enough to cause a difference in the condensing conditions inside the tower or that low concentrations of sodium have no effect on the condensing characteristics. The data obtained for the cadmium was found to be not much different from the mercury data and again in poor agreement with the Nusselt relationship.

The apparatus consisted of a small boiler with a reflux condenser. The boiler was surrounded with a guard heater and the heat for vaporization was supplied by a central silicon carbide heater. There was an access line for filling the apparatus; this line was also used for the evacuation of the apparatus. Temperature measurements were taken at several points along the reflux tower and there was a means by which the vapor temperature was measured both in the boiler and tower vapor space. The latter was accomplished by thermocouple wells that extended into the vapor spaces. Power was measured by wattmeters. Type 304 stainless steel was used throughout the whole apparatus.

REVIEW OF LITERATURE

Theoretical Considerations

The theoretical Nusselt relation for heat conduction through a condensate film for condensation on a vertical surface is given by the equation (11, p. 331):

$$h = 0.943\left(\frac{k^3\rho^2 g\lambda}{L\mu\Delta t}\right)^{\frac{1}{4}*} \quad ....(1)$$

There are a number of assumptions made in the derivation of this relation that make it difficult to apply in an actual situation. The condensate film is considered to be of uniform thickness throughout the area of consideration; the flow of the condensate is considered to be laminar and without irregularities in the line of flow. The flow is considered to be due to gravity effects only. Probably the most important assumption is that the condensation takes place entirely by a filmwise process, and that the film completely wets the surface. It is further assumed that the film temperature is uniform throughout the length of the surface and that the temperature gradient through the condensate film is linear.

Dropwise condensation takes place when the condensing surface is not wetted by the condensate or is contaminated either by chance or by the use of a promoter which does not allow the condensate to wet the surface. It has been

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* A nomenclature section defining these symbols appears on page 48.

found that values of the condensing coefficient are somewhat higher for dropwise than for filmwise condensation. The liquid forms a contact angle with the surface (measured tangent to the bottom edge of the drop through the liquid). If this angle is less than 50° the drops do not spread evenly and the surface area becomes covered by a film of the condensate (1, p. 451). A study of dropwise condensation would reveal a mechanism where the drops form on the surface in a random fashion and are more or less uniform size and shape. As the drops grow from condensation on their surface and by coalescence with other drops nearby, they reach a critical size at which they no longer adhere to the wall. At this point, the drop rolls down the wall sweeping other drops along with it. Thus a path is cleared and the process starts over again. Dropwise condensation of steam has been investigated by Fatica and Katz (3, p. 161). A study of mercury condensing on vertical plates has been accomplished by Misra and Bonilla (11).

The kinetic theory of condensation imparts the mechanism to condensing vapors in that a vapor in contact with its condensate, where the condensate is below the dew point of the vapor, will condense on the surface of the condensate. This appears to occur on a molecular scale where the molecules of less than average kinetic energy have a greater probability of entering the surface of the liquid and staying there. In the case of many polar molecules it appears that the individual molecules tend to form groups of the less energetic individuals and with decreased average kinetic energy enter the liquid surface and condense there.

The mass rate of flow of the molecules toward the condensing surface is given by the kinetic theory of gases to be: $G = P\sqrt{M/2\pi RT}$ .... (2). In an equlibrium situation, the rate of evaporation is the same as that of condensation. Thus equation (2) also expresses the evaporation rate if the liquid interface temperature and equlibrium pressure are used. The net rate of condensation is the difference between the rates of condensation and evaporation. $\left(\frac{q}{A}\right)_{net} = \left(\frac{M}{2\pi R}\right)^{\frac{1}{2}} \left[\left(\frac{PH}{T^{\frac{1}{2}}}\right)_v - \left(\frac{PH}{T^{\frac{1}{2}}}\right)_i\right]$ ..... (3). The result of multiplication by enthalpy of the bulk of the vapor (H_v) and the enthalpy of the vapor at the interface (H_i) with the terms respectively in v and i in equation (3) gives the condensation rate directly in heat units.

The kinetic theory assumes that when a molecule strikes a surface it condenses and is never reflected. For a contaminated surface this is not true. The condensation coefficient, α, must therefore be used in order to account for reflection from contaminated surfaces. Thus equation (2) becomes: $G = \alpha P\sqrt{M/2\pi RT}$ .... (4).

Values of α as low as 1/2,000 have been reported for a contaminated mercury droplet (7, p. 13). Investigations show that $\alpha = 1$ for a clean surface of mercury. For filmwise condensation on a clean surface, the assumption of $\alpha = 1$ is acceptable; although this assumption is somewhat in error for dropwise condensation due to the exposed surface of the condenser.

Rohsenow, Webber, and Ling have presented a theoretical study of the effects of vapor velocity on film condensation (14). The workers present plots of the Reynolds number vs $\frac{h}{k}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ for Prandtl numbers ranging from 0.01 to 10.0. Reynolds numbers range from 10 to 100,000. Lines of constant contact shear stress between the vapor and the liquid film are presented on each plot, where the parameter $\tau_v^* = \frac{g_o \tau_v}{g(\rho - \rho_v)\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}}$ .... (5) varies from zero to 50.

The consequence of this analysis is to give higher values to the quantity $\frac{h}{k}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ at higher shear stresses, and thus the condensing heat transfer coefficient is larger. This analysis helps explain the larger values of the heat transfer coefficient often obtained in an experimental study; as experimental values of the heat transfer coefficient are often larger than the values predicted by equation (1). A plot of this type for zero shear is presented in Figure 9.

These workers considered the usual variables employed in the derivation of the Nusselt relationship, but they also considered the variables that would effect the shear characteristics between the liquid and vapor, namely: the fluid and vapor velocities, the vapor density, and a variable film thickness. These workers considered both the laminar and turbulent regions of the condensate film.

Experimental Considerations

Misra and Bonilla (12, p. 17) have studied heat transfer by condensing mercury vapor up to one atmosphere pressure. A limited study was also made of sodium vapor condensation, but the data are for a tube inclined at an angle of 45^{o} only. Other than a small amount of data published by the General Electric Company on their mercury power plants, the article of Misra and Bonilla is the only published material in the field of heat transfer by condensing liquid metal vapors.

In the study conducted by these workers, values of the condensing coefficient were found to be only 5 to 15% of the predicted values from the Nusselt relation. The investigators were unable to explain the low results. The deviations from the Nusselt assumptions that were observed or implied would tend to give values higher than the Nusselt relation rather than lower values. McAdams (11, p. 332-338) lists various factors which would make the assumptions in the Nusselt relationship invalid.

Some of these factors are:

1. Effect of vapor velocity. A high upflow of vapor would tend to cause a hold up in the condensate flow and therefore a thick film would be encountered for heat transfer and thus give a low value of the condensing coefficient. When there is a strong downflow of vapor,

the friction between the vapor and the condensate film causes a thinning of the condensate film resulting in high values for the coefficient. Both effects are noticeable only at high vapor velocities.

2. The effect of noncondensible gas. This was found to lower the value of the heat transfer coefficient linearly with an increasing weight fraction of noncondensibles. The study of the effect of noncondensibles on condensation has been carried out mostly with a steam-air mixture.

3. The effect of turbulence. This appears to be pronounced for a value of $\frac{4\Gamma}{\mu}$ greater than 2,000 (Figure 9). As the condensate layer and vapor adjacent to this layer become more turbulent, the value of the heat transfer coefficient increases logarithmically as the log of $\frac{4\Gamma}{\mu}$ increases.

4. Ripples in the surface. McAdams suggests that the occurrence of ripples in the surface of the condensate film gives a variation in the thickness of the condensate and therefore a larger average value of k/Film thickness which would lead to a value of the condensing coefficient somewhat larger than the value predicted by the Nusselt relation (11, p. 330).

5. Dropwise condensation. An important factor effecting the predicted values of the heat transfer coefficient is the occurrence of dropwise condensation. If dropwise

condensation takes place, the value of the coefficient is almost always higher due to the additive effects of turbulence and thinner average film thickness (1, p. 452).

6. Variation of fluidity of the film. McAdams suggests that the variation of condensate fluidity with temperature would effect the predicted value of the condensing coefficient, but this would only be important in the case of a large temperature gradient through the condensate film which is usually not the case.

7. Contamination. Contamination of the condensate film would be a contributing factor to a lower value of the condensing coefficient, particularly if the contaminant is concentrated on the surface of the film.

Promoters

A promoter is a substance that changes the characteristics of a condensing vapor. Promoters are used in industry to produce higher heat transfer coefficients by promoting dropwise condensation. (eg. benzyl mercaptan, octyl thiocyanate, and oleic acid). If the surface contaminant reduces the interfacial tension sufficiently to render the surface nonwettable, the condensate will collect in drops that grow in size until downward forces cause them to roll down the surface.

A promoter that causes the condensate to wet the surface would cause correspondingly lower heat transfer coefficients. Mercury with small amounts of sodium in it tends to wet the surface of a metalic container. Lyon (5, p. 85) found that mercury exhibited better wetting characteristics when small amounts of sodium were present in his boiling apparatus. If sodium was present in the mercury vapor during condensation, a greater wetting could take place and thus cause lower condensing coefficients.

Misra and Bonilla (12, p. 17) found that mercury condênsation on stainless steel was predominately dropwise. These workers measured heat transfer coefficients for condensing mercury and sodium vapors with the following results: For mercury heat flux varied from about 25,000 Btu/hr ft^2 at 0.5 lb/in^2 abs. with air cooling to about 750,000 at 15 lb/in^2 abs. with water cooling. The heat transfer coefficient ranged from about 3,000 to about 10,000 Btu/hr ft^2 ^oF for film-type condensation and from about 4,000 to over 50,000 for dropwise condensation. For sodium the heat flux varied from about 60,000 Btu/hr ft^2 to about 100,000 giving a heat transfer coefficient ranging from 11,000 to 13,000 Btu/hr ft^2 ^oF. This was carried out with the vapor condensing on the outside of a tube inclined at a 45^o angle.

THE APPARATUS

An apparatus was designed to measure the condensing coefficients of liquid metal vapor. It was necessary to build an apparatus to withstand the high temperature and conditions imposed by this vapor. A survey of the literature indicated that type 304 stainless steel was a suitable material at moderate pressures up to 2,000 °F. Consequently, the apparatus was constructed entirely from type 304 stainless steel, and it proved satisfactory under the experimental conditions encountered.

Construction of the Boiler and the Condenser

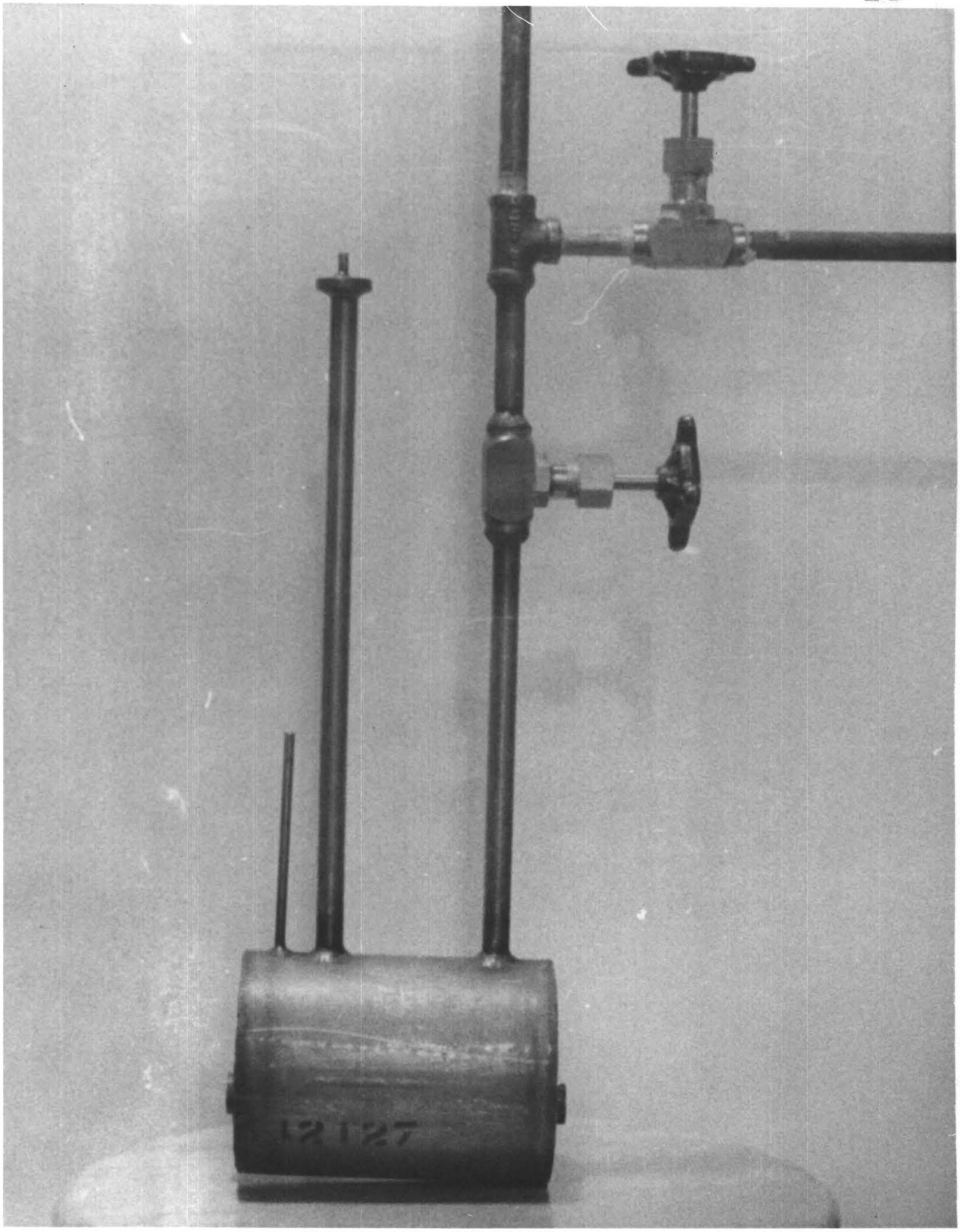
The main apparatus was the boiler and condenser with which the liquid metal was vaporized and condensed. This apparatus was equipped with a means of heating the liquid metal, sufficient thermocouples to determine all important temperatures, and necessary connections for introducing the mercury and evacuating the system.

The boiler shell consisted of a 4" OD, 3/16" wall seamless tubing cut to a length of 5 5/8". This boiler shell was closed with end plates 3/8" thick. A boiler tube made of 3/4" OD, 16 Bwg welded tubing was inserted through the end plates a distance of 1 3/8" from the bottom of the boiler shell. This boiler tube contained an electric heater for boiling the liquid metal. The boiler tube was positioned so that it would not cause local heating in the bottom of the shell nor cause vigorous boiling at the liquid surface. The boiler tube extended 1/4" on each side of the apparatus to protect the heating element. The overall length of the boiler shell was 5 5/8".

One end of the boiler shell was shouldered 1/16" deep and 1/4" into the wall of the shell in order to allow a strong anchor for this end of the boiler shell end piece. The other end of the boiler shell was not shouldered and the 3 5/8" ID remained unchanged in order to allow for expansion of the boiler shell and tube during the heating and cooling they experienced when the welding was done. The joint between this boiler shell end and the boiler shell was the last joint to be welded.

Access to the boiler tube was provided by the steel pipe shown in Figure 1. This line contains a 1/2" needle valve 8" above the boiler. The needle valve was of type 316 stainless steel due to the unavailability of type 304. Above this valve was a tee, one branch of which led to a vacuum pump and the other to a nitrogen cylinder.

A reflux condenser was constructed of a 1/2" OD,16 Bwg stainless steel tube 12" in length with an inside heat transfer area of 0.0826 square ft. considering a cooled



THE BOILER & CONDENSER
FIGURE 1

length of 10.25". It was mounted on the boiler as shown in Figure 1. Three thermocouples were positioned at distances of 4", 8" and 11½" from the boiler shell to measure the skin temperature of the condenser. The thermocouples were inserted into 0.012" grooves cut vertically into the exterior of the condenser. These thermocouples were held in place by thin copper clamps, and insulated from any metal contact except at the bi-metalic junction by 10 mil. pure mica insulation. Heat was removed from the condenser by natural convection. Forced convection was attempted using a ¼ hp. blower, but excessive local cooling was encountered which gave erroneous results.

Two thermocouples were installed in the apparatus. One thermocouple well extended ½" into the boiler shell and permitted the measurement of the temperature of the vapor above the boiling liquid metal. The other thermocouple well extended into the reflux condenser to a depth of 8". The thermocouple in this well was movable to allow measurement of the temperature at various points along the length of the reflux condenser. A third thermocouple was placed in the air space between the guard heater and the boiler shell to measure the temperature in this space. Chromel-alumel thermocouples (22 B & S) were used exclusively as they would best withstand the high temperatures encountered. Temperature measurements were made with Leeds & Northrup portable potentiometer. An ice bath at 32 ^{o}F. was used for the cold junction.

The entire apparatus was welded throughout using a heli-arc welding process with type 18-8 welding rods.

Heat Supply

The heat for vaporizing the metal in the boiler was provided by a 1/2" diameter silicon carbide "Globar" heating element 17" long with a heated length of 6". The heating elements were manufactured by the Carborundum Company of Niagra Falls, N.Y. The Globar elements had a nominal resistance of 1.25 ohms. The heating element was inserted in the boiler tube so that the heated length was completely covered by the boiler tube. The heating element was protected from short-circuiting against the metal surface of the boiler tube by small ceramic feet glued to the heating element with Sauereisen Cement.

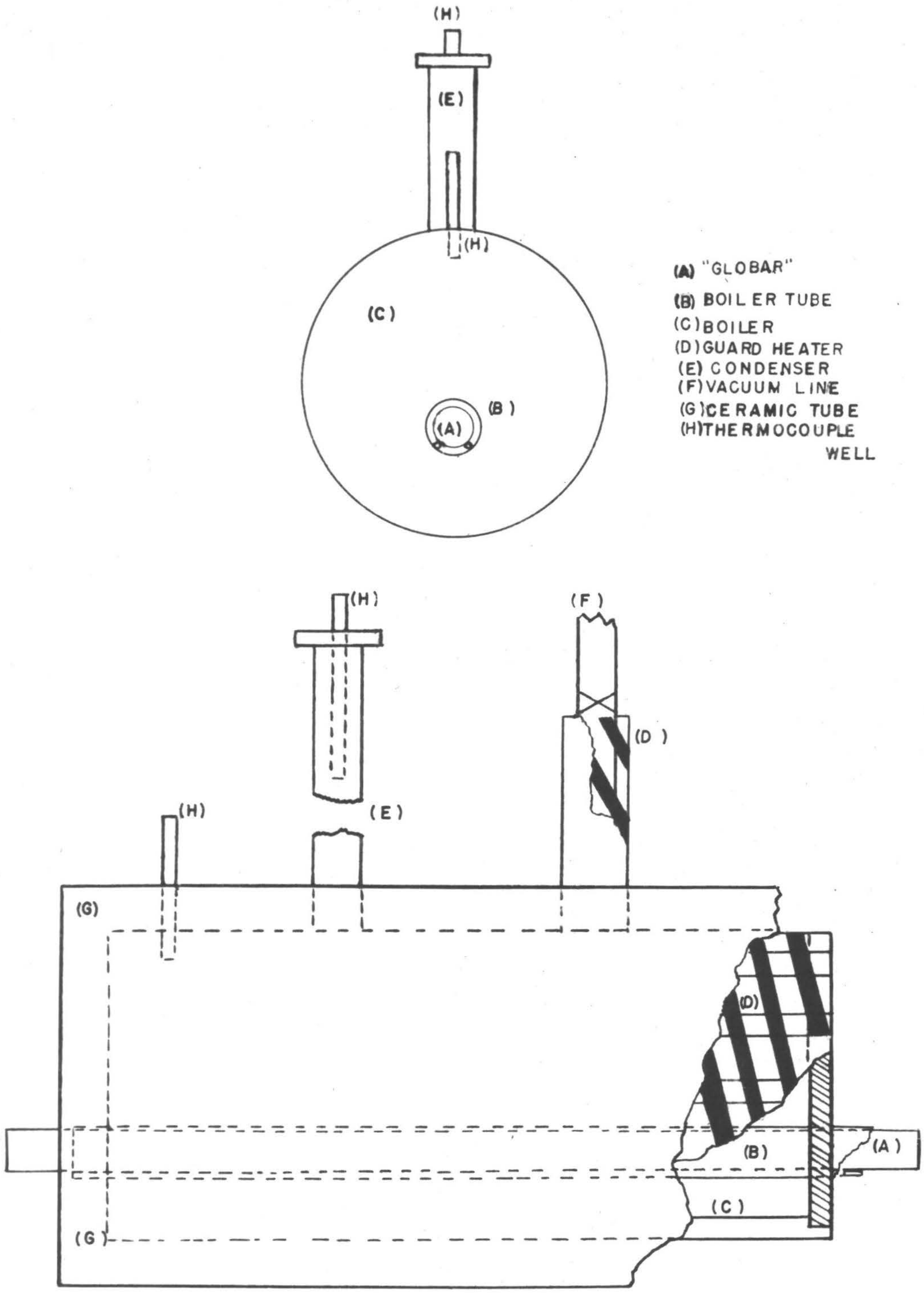
The element was connected to a 220 volt A. C. supply through a 220 volt-7.5 KVA Powerstat. Suitable control of the power to the element could be obtained by this arrangement. The power measurement was accomplished by the use of a Jewel 20 KW direct reading wattmeter. The heating element was supported at its terminals by an asbestos brick through which the element was inserted. The terminal straps and clamps were attached on the heating element at the point where the element protrudes through the half inch hole in the brick.

Insulation

In order to control the heat losses from the boiler shell, it was surrounded with a nichrome strip guard heater wound around ceramic spacers. This entire assembly was inserted into a 6" diameter, 8" long ceramic tube. The ends of the tube were covered with magnesia insulation to a depth of 1" leaving only the 3/4" inch boiler tube exposed. The guard heater was maintained at the same temperature as the interior of the boiler shell, and therefore allowed no heat losses through the boiler shell. The heat losses from the nitrogen-vacuum line and valve are controlled by an extention of the guard heater and a covering of magnesia insulation.

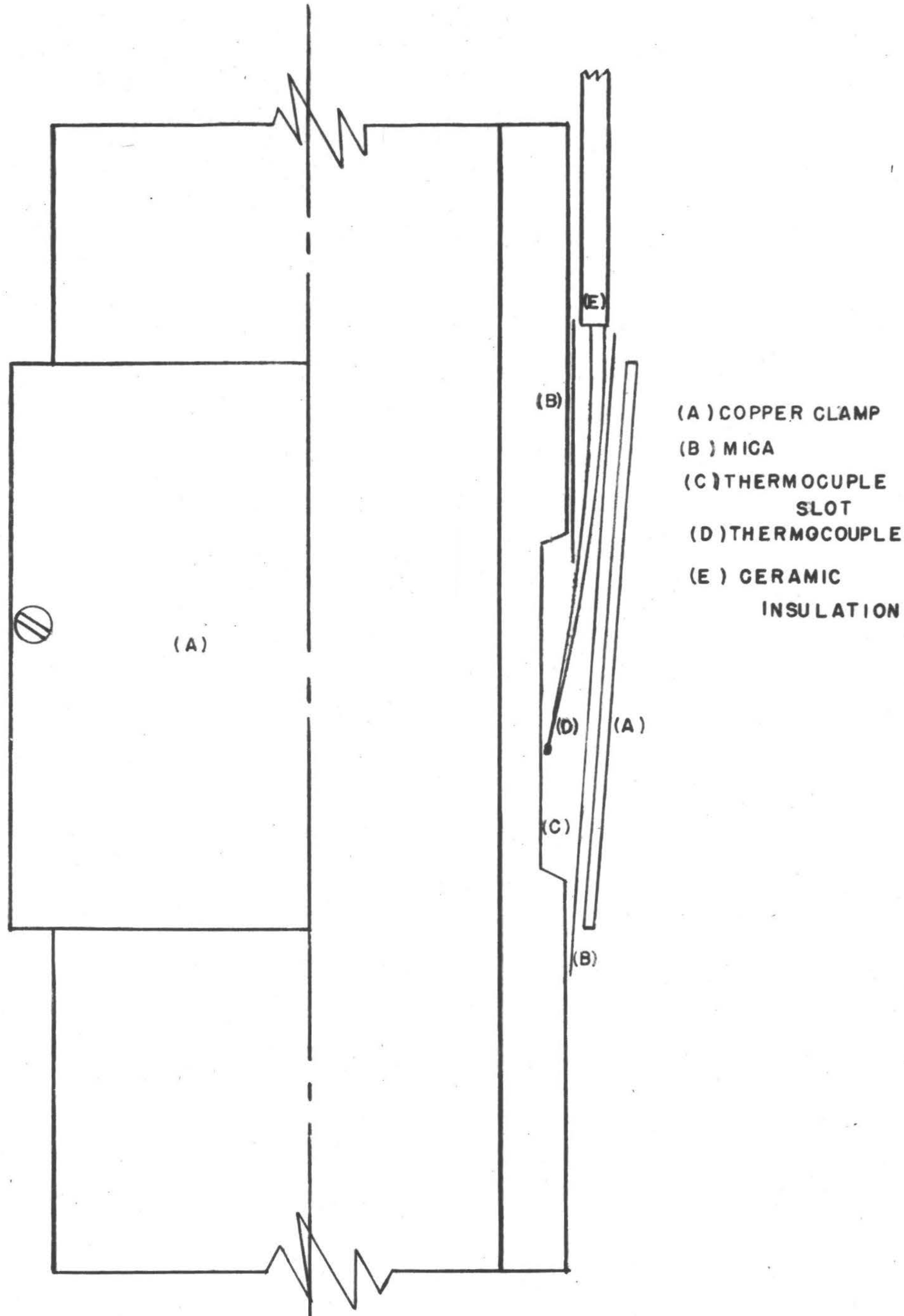
Mounting

The apparatus was mounted on a steel stand and was held in place by the two asbestos bricks which support the carbide heater. These bricks were supported by the upright ends of the mounting stand. The ceramic tube that holds the apparatus fits snugly between the two asbestos bricks so that the air space heated by the guard heater is essentially stagnant. These bricks tend to stop any chimney effects from the central heating element.



BOILER, CONDENSER, and GUARD HEATER

FIGURE 2



THERMOCOUPLE ASSEMBLY

FIGURE 3

THE EXPERIMENTAL METHOD

General Operating Procedure

Before a run was started, the thermocouple clamps on the condenser were checked for tightness. The condenser vapor temperature thermocouple along with the vapor space and guard heater thermocouples were removed and examined visually for any break in the ceramic insulation or a broken junction. The thermocouples and the mica insulation used on the condenser were usually changed after each run during the cadmium study as the high temperatures tended to destroy the insulation and burn out the thermocouple junctions.

The apparatus was evacuated for at least an hour before a run was started. In the case of the water, a small amount of water vapor was drawn off each time to insure the removal of any noncondensibles. The mercury systems were usually evacuated at an elevated temperature to remove any noncondensibles. This temperature was not so high as to allow any evaporation of the mercury. During the water study a nitrogen cover was used when the apparatus was not in use. An argon cover was used with the mercury-sodium systems when the apparatus was not in use. When the pure mercury or cadmium was studied, the vacuum pump was operated continuously. The valve to the boiler was not opened in either case until the liquid metal has cooled to a temperature where the vacuum would cause no evaporation of the metal contained in the boiler.

The water was charged by admitting distilled water into the previously evacuated boiler through the vacuum line. The mercury and mercury-sodium systems were charged in a similar manner. The cadmium was charged by drilling a hole in the boiler wall and charging the cadmium directly into the boiler cavity in stick form as it was obtained from the manufacturer. Chemically pure cadmium was used in the cadmium study and filtered mercury and chemically pure sodium were used in the mercury and mercury-sodium studies.

After the thermocouples were checked and the vacuum was considered complete, the valve leading into the boiler was closed. The vacuum remained on to eliminate any air that might accumulate in the upper line due to leakings in the system.

The guard heater was then turned on, but no power was applied until the body of the apparatus was checked for a possible ground in the guard heater. If none was detected, the Globar heater was turned on and the apparatus was again checked for a possible ground in the carbide heater due to a break in the insulation or faulty centering of this heater.

The guard heater was turned on to about 1.7 KW initially. This power was held constant until the desired vapor temperature was obtained in the condenser. When an attempt to approach equlibrium was made, the power in the guard heater was reduced to a level that was sufficient to maintain the air space temperature at the same value as the vapor temperature. This power load varied from about 200 watts for the water study to about 450 watts for the cadmium study. An aluminum foil covering was added to the outside of the ceramic cylinder for the cadmium study to reduce the load on the guard heater.

After the Globar heater was checked for possible shortcircuits, it was turned to an initial power of about 1 KW; after boiling had commenced, the power was raised to 1.5 KW. The latter was done in order to force the heated vapor into the column. This procedure helped to condition the column to a uniform temperature and made the approach to equlibrium quicker. Because this initial heating was vigorous, the vapor that entered the column first tended to be superheated. If the initial heating had been conducted more slowly, the exceptionally fast condensation rate due to the initially cold tower would sweep the remaining vapor out of the condenser. If slow initial heating was used, several hours were required to reach an equlibrium situation. With vigorous initial heating, an equlibrium situation could be reached in about ½ hour after the central and guard heater power was reduced.

When the desired vapor temperature was reached and the temperatures in the vapor space in the boiler and the tower vapor temperature were the same, the power was reduced in the guard heater and central heater. When the various tower skin temperatures corresponded and the regulation of the guard heater had produced an air space temperature near to the temperature of the vapor, the time was noted and, if no change in these temperatures was noted during a five minute period, the various thermocouple readings were recorded and the power to the central heater was also recorded. At this point, the power to the central heater was changed and the guard heater regulated to correspond to the new vapor space temperature. After equlibrium was again reached and a proper waiting time had passed, another set of data was recorded.

After several sets of data were taken, the power was shut off and the apparatus was allowed to cool. This cooling was often hastened with the aid of a blower. After the apparatus had cooled to a point where its contents were no longer volatile, the vacuum line into the boiler was opened and this was either left on, or the gas cover was applied.

Heat Removal

Heat removal was accomplished by natural convection. A blower was used in some runs, but irregular thermocouple readings indicated uneven cooling.

Processing of Data

Calculations

A heat balance equation was employed to find the temperature of the inside wall of the condenser. By means of this equation the inside wall temperature may be calculated from which Δt across the condensing film could be determined using the vapor temperature as the temperature of the inside film edge. For heat transfer through a wall of a circular pipe:

$$q = \frac{2\pi r_{lnm} L \quad k (t_1 - t_2)}{\Delta \quad X} \qquad \ldots\ldots (6)$$

from which:

$$t_1 = \frac{q \Delta X}{2\pi r_{lnm} Lk} + t_2 \qquad \ldots\ldots (6a)$$

where:

t_1 = outside film temperature = inside wall temperature

and t_2 = outside wall temperature.

where:

$$r_{lnm} = \frac{r_1 - r_2}{\ln \frac{r_1}{r_2}} \qquad \ldots\ldots (7)$$

r_1 = inside radius
r_2 = outside radius to thermocouple slot

The mean heat transfer coefficients of the condensing vapors were calculated from:

$$q = hA\Delta t = h\,A\,(t_2 - t_1) \quad \ldots\ldots\ldots \ (8)$$

where t_2 = inside film temperature = vapor temperature

t_1 = outside film temperature

The theoretical heat transfer coefficients were calculated from equation (1) for the systems studied and these were compared with the experimental results.

The properties of the condensing fluid were evaluated at the vapor temperature. Properties of the various liquid metals studied are tabulated in Appendix 3. Not too good agreement is shown among the various references reporting physical properties. For this reason and because the temperature differences were usually small the film temperature $t_s - 3/4\ (\Delta t)$ as defined in McAdams (11, p. 336) was not used in evaluating the fluid properties.

The method of Rohsenow, Webber, and Ling was used in a calculation to correlate the data in the manner of the theoretical treatment in this paper (14, p. 1630). Values of $4\frac{\Gamma}{\mu}$ and $\frac{h}{K}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ were calculated from the physical data given in the appendix. The line of zero contact shear was used in the comparison; an attempt was not made to evaluate the contact shear for the experimental data.

A study was also made to determine if the vapor velocity had an effect on the heat transfer coefficients.

Values of $\frac{D\,G_m}{\mu}\left(\frac{\rho_L}{\rho_v}\right)$ and $\frac{h\,(N_{Pr})^{0.5}}{c_p\,G_m}$ (11, p. 336) and (2, p. 25) were calculated for the mercury data and were plotted versus each other. The physical data used for this calculation is given in Appendix 3.

EXPERIMENTAL DATA

TABLE I

Summary Table

Table 1 gives a summary of the experimental data obtained in this investigation, giving systems studied and ranges of variables covered

	Δt °F		h Btu/°F hr ft^2		Heat Flux Btu/hr ft^2		Temperature Range °F	
	Min	Max	Max	Min	Max	Min	Min	Max
water	1.0	29.6	10.600	129	16,900	830	243	326
mercury	0.55	68.2	52,600	380	63,600	7,220	585	706
mercury 0.3% sodium	4.6	38.8	6,990	744	43,300	6,190	542	725
mercury 1.0% sodium	0.5	40.0	69,000	371	43,300	6,190	533	719
cadmium	1.8	69.7	12,600	211	49,500	8,230	1,178	1,426

RESULTS

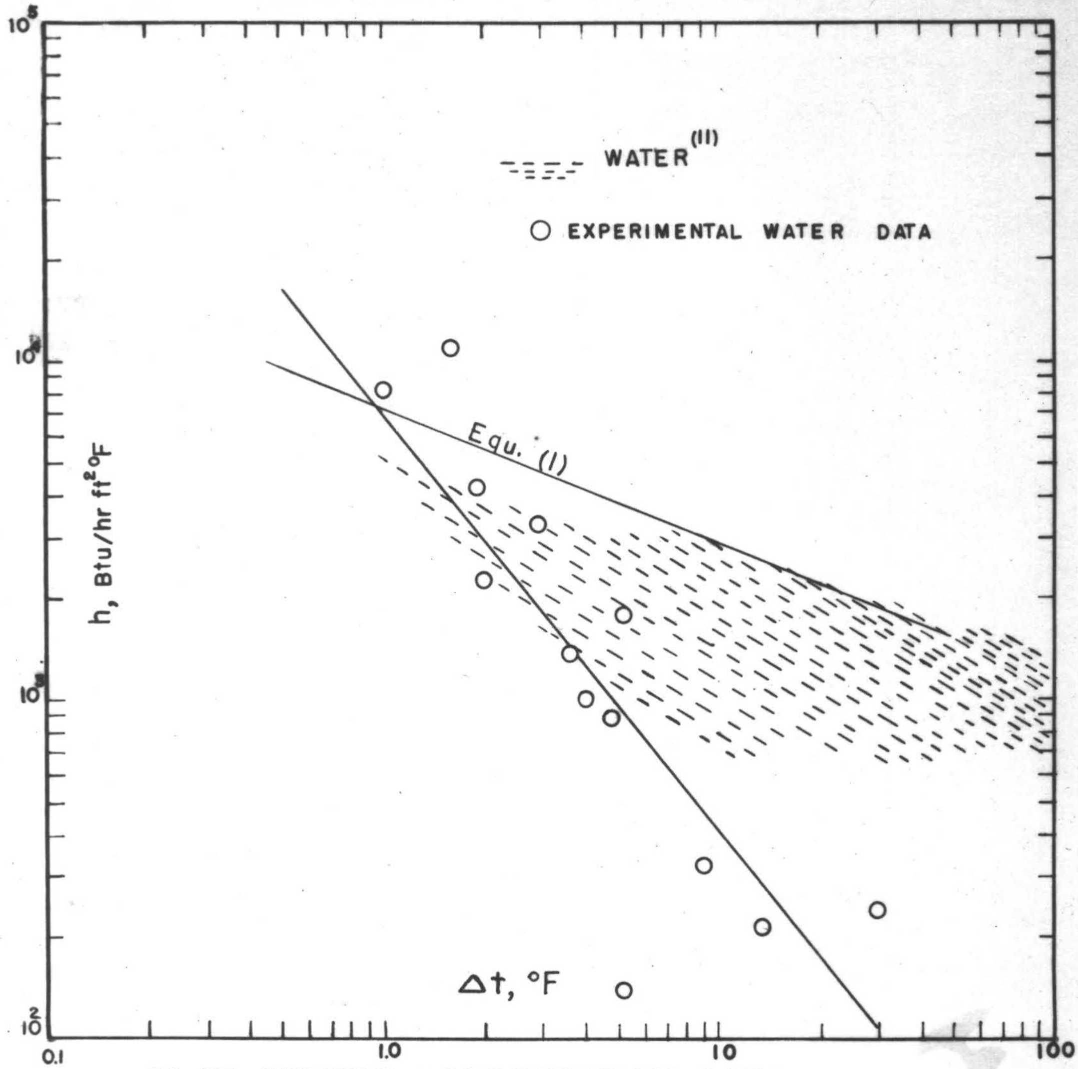
Correlation of Data

The variation of the heat transfer coefficients with temperature difference was first studied for each system as shown in Figures 4-8.

Water

The data for water are shown in Figure 4. The shaded portion in Figure 4 covers the range of experimental data obtained on water and listed by McAdams (11, p. 333). In the present work the condensing coefficients obtained for water ranged from 24,100 Btu/hr ft^2 ^oF. to 217, and the Δt range was from 0.7 ^oF. to 29.6 ^oF. Water data were taken between 250 and 325 ^oF. and the heat fluxes varied from 830 Btu/hr ft^2 to 16,900.

The heat transfer coefficients for the medium and high heat fluxes were in good agreement with other experimental values and in fair agreement with the Nusselt relationship. The condensing coefficients calculated for the low heat fluxes were much lower than the values predicted by the Nusselt relationship and the values obtained by other experimenters. It is possible that these low heat fluxes gave such low values of the condensing coefficients due to the possibility that the heat



PLOT of WATER CONDENSATION DATA

FIGURE 4

loss was due to natural convection rather than condensation or that the effective heat transfer area was smaller than expected.

Mercury

The data for condensing pure mercury are shown in Figure 5. They are in good agreement with the condensing data of Misra and Bonilla (12, p. 17) for air cooled condensers.

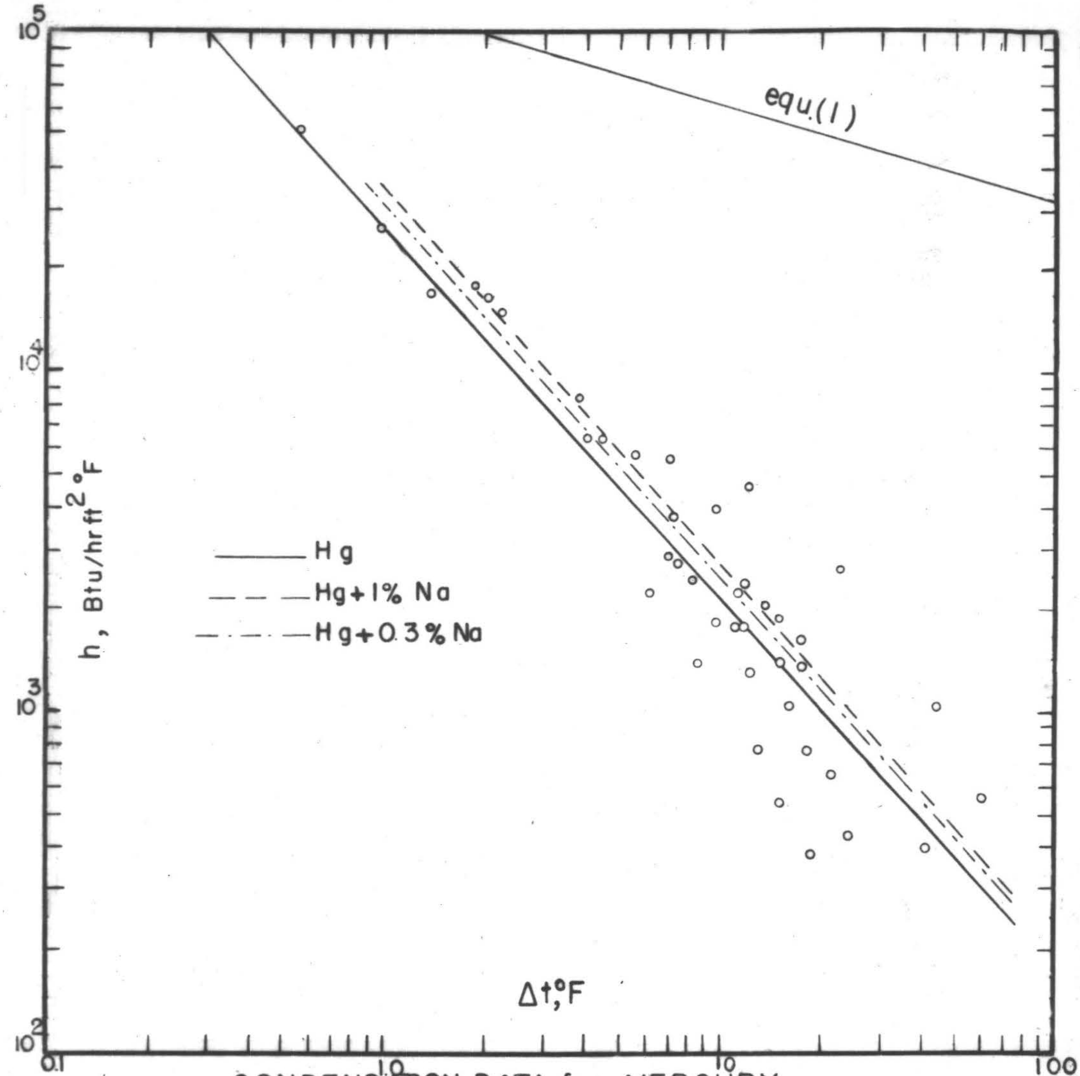
The data obtained for mercury, however, were found to be in poor agreement with the Nusselt equation. Misra and Bonilla reported similar results. The equation for the condensing coefficients of mercury as a function of temperature drop through the film is:

$$h = 28{,}200\ \Delta t^{-1.039} \quad \ldots\ldots\ (9)$$

Values of coefficients varied from 52,600 to 380 Btu/hr ft^2 $^\circ$F. and Δt range from 0.55 to 68.2 $^\circ$F. Mercury data were taken at 585 to 700°F. Heat fluxes varied from 7,220 to 63,600 Btu/hr ft^2.

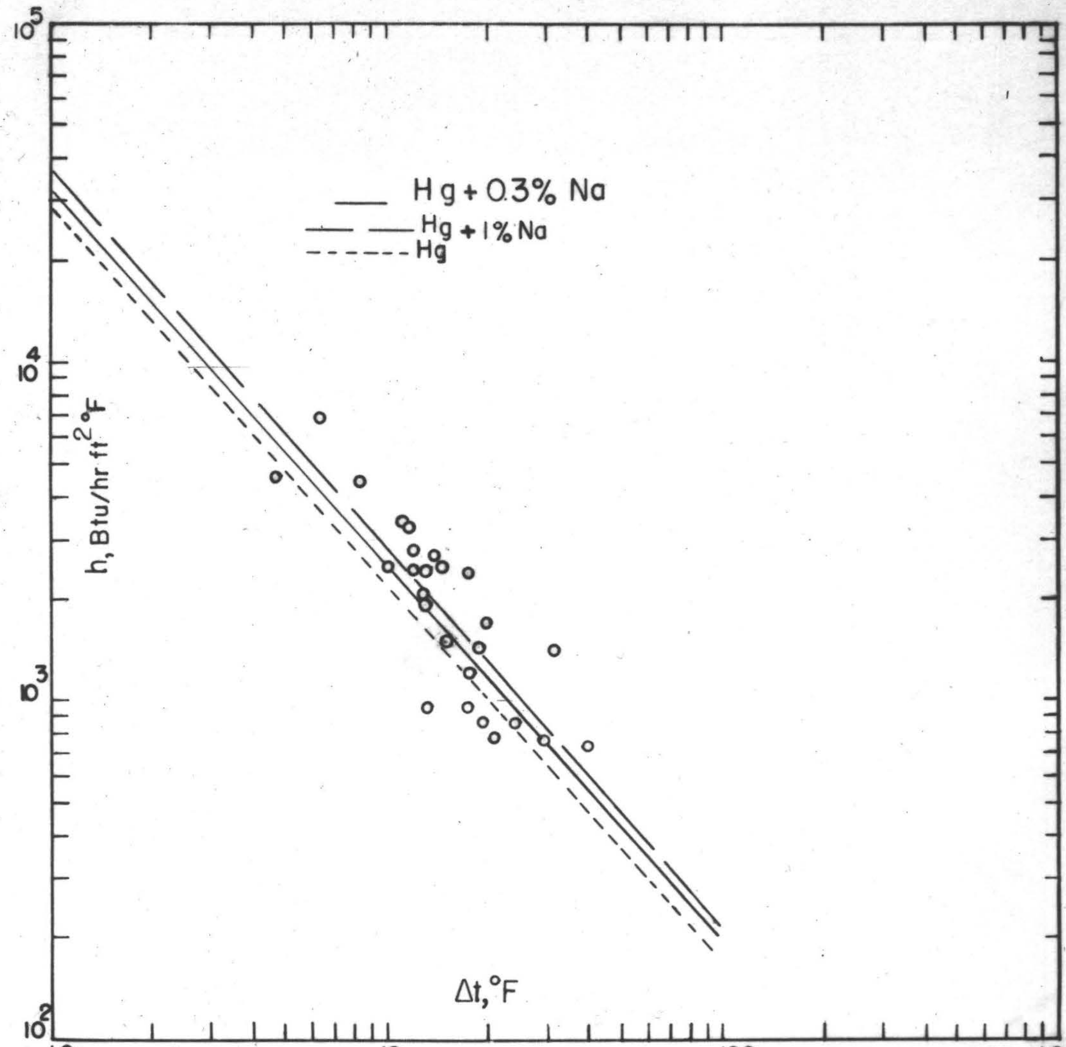
Mercury and Sodium

The plots of the condensing coefficients for mercury with 0.3% sodium and with 1.0% sodium vs Δ t are shown in Figures 6 and 7. The results for these two solutions were found to be almost identical with those for pure



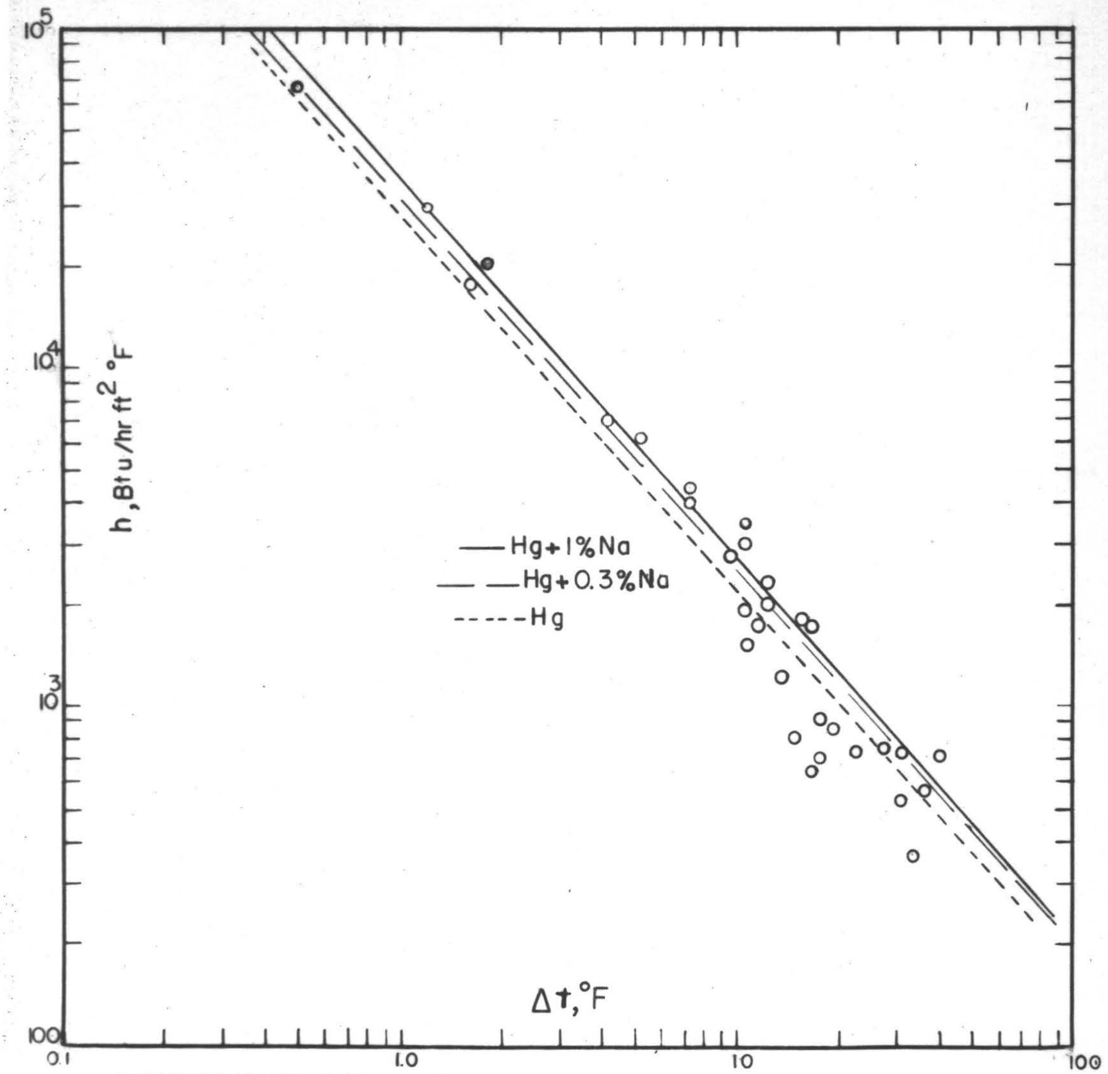
CONDENSATION DATA for MERCURY

FIGURE 5



CONDENSATION DATA for MERCURY plus 0.3% SODIUM

FIGURE 6



CONDENSATION DATA for MERCURY plus 1.0% SODIUM

FIGURE 7

mercury. The equations for the mercury and sodium systems were only slightly different than the equations for pure mercury:

Mercury plus 0.3% sodium: $h = 32{,}300\ \Delta t^{-1.10}$ ..(10)

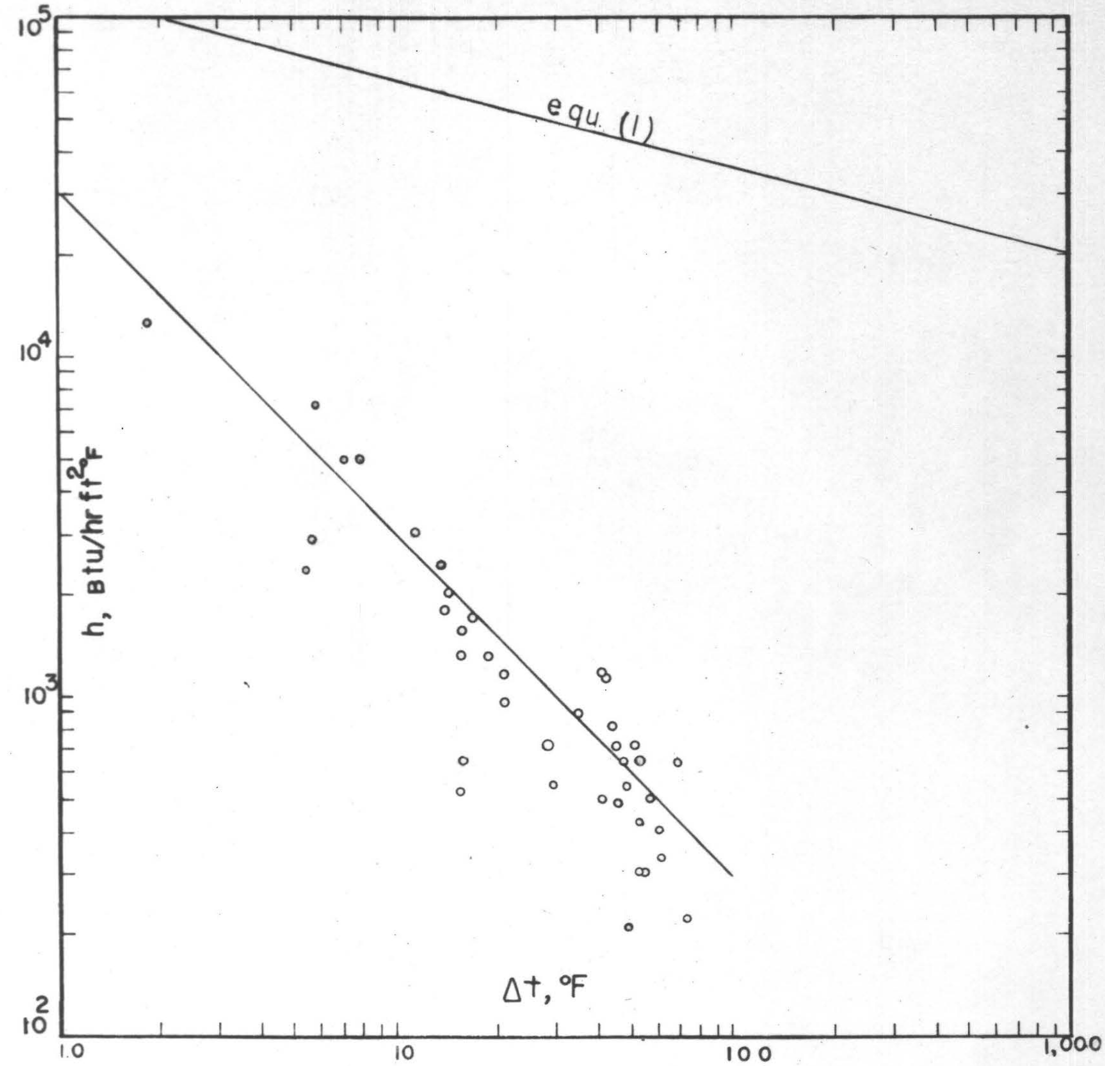
Mercury plus 1.0% sodium: $h = 36{,}700\ \Delta t^{-1.12}$ ..(11)

The condensing coefficients for the solution with 0.3% sodium varied from 6,990 to 744 Btu/hr ft^2 $^oF.$, with a Δt range of 4.6 $^oF.$ to 38.8, while those for the 1.0% sodium solution varied from 69,000 to 371 Btu/hr ft^2 $^oF.$, with a Δt variation of 0.50 to 40.0 $^oF.$ Mercury-sodium data were taken in about the same temperature range as the pure mercury data. Heat fluxes varied from 6,190 to 43,300 Btu/hr ft^2.

It may be concluded that sodium present in small amounts does not change the condensing characteristics of mercury vapor. This is probably due to the low volatility of the sodium at the normal boiling point of mercury so that none is present in the vapor, or due to the possibility that sodium present in mercury vapor does not change the nature of the condensing process.

Cadmium

The plot of the heat transfer coefficients vs Δt for cadmium along with the comparison to the Nusselt relationship is given in Figure 8. The data for the cadmium study gave the following relationship between



CADMIUM CONDENSATION DATA

FIGURE 8

the heat transfer coefficient and Δt:

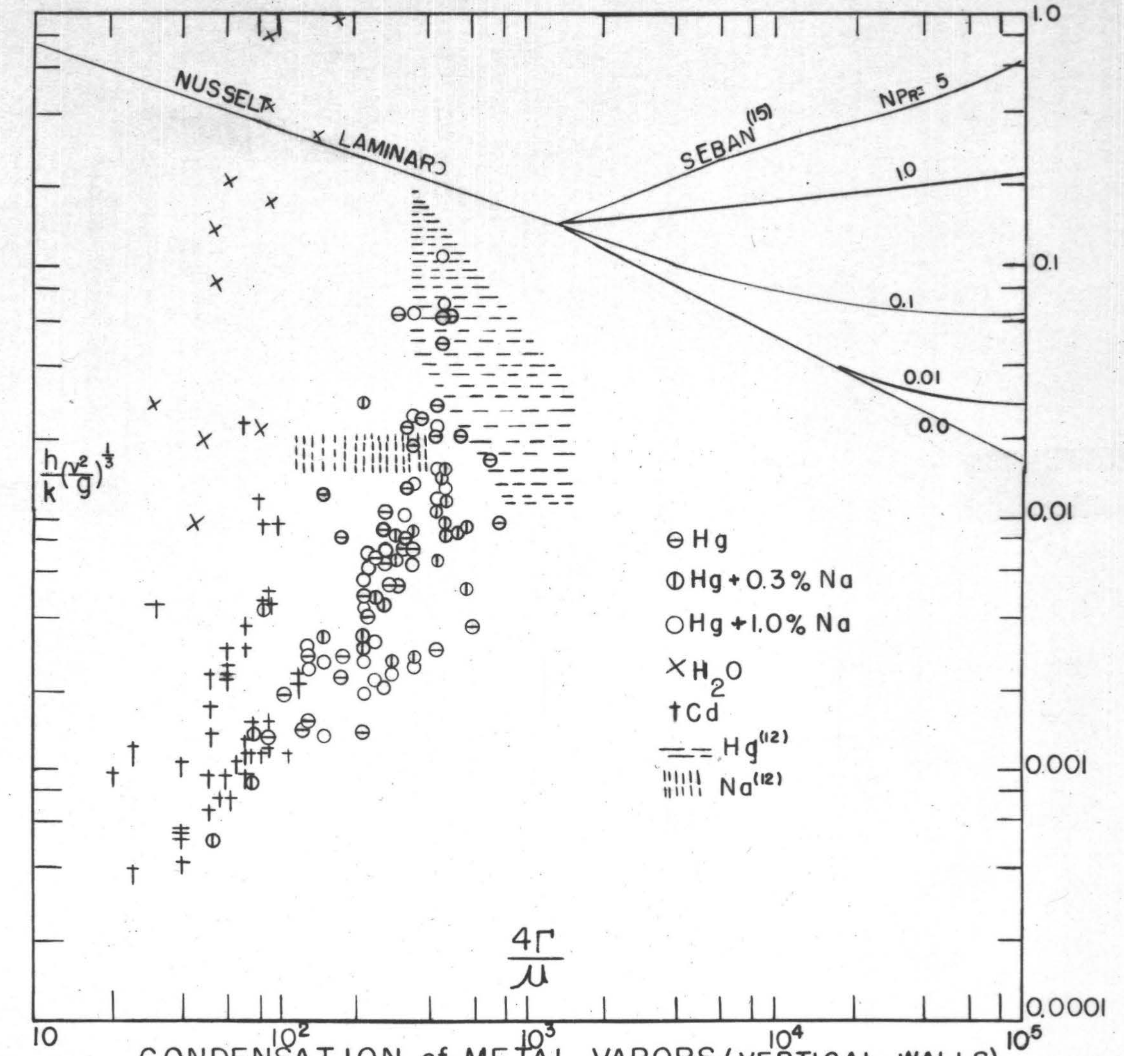
$$h = 30,400 \quad \Delta t^{-1.00} \quad \ldots\ldots\ldots (12)$$

These results are very similar to data obtained on mercury and mercury-sodium. Variations of Δt from 1.8 °F. to 69.7 °F. were obtained; and the condensing coefficients varied from 211 to 12,600 Btu/hr ft^2 °F. A certain amount of difficulty was encountered in obtaining good agreement for the three thermocouple readings on the tower surface. This was due to the deterioration of the thermocouples and the thermocouple insulation during the various runs. Heat fluxes varied from 3,220 to 49,300 Btu/hr ft^2, and the condensing temperature range was from 1,178 °F. to 1,426 °F.

As with mercury, the cadmium data yielded much lower condensing coefficients than were predicted from the Nusselt relationship.

Dimensionless Correlation

In Figure 9, $\frac{h}{k}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ is plotted versus $\frac{4\Gamma}{\mu}$ for all the experimental data obtained on all systems. Up to $\frac{4\Gamma}{\mu}$ 2,000 the curve represents the Nusselt equation. Above this value of $\frac{4\Gamma}{\mu}$ an individual curve is obtained for each Prandtl number. This is the region where the condensing film is turbulent. These curves apply for zero vapor velocity and have been obtained analytically by



CONDENSATION of METAL VAPORS (VERTICAL WALLS)

FIGURE 9

Seban (15, p. 300) and Rohsenow and coworkers (14, p. 1630). The mercury and sodium data of Misra and Bonilla (12, p. 20) are included in this plot.

It may be seen that the water data of medium and high heat fluxes gives reasonable agreement with the zero shear laminar flow line whereas the low heat flux values do not agree with the theoretical line.

It may also be seen that the data obtained for mercury and mercury-sodium in this investigation fall in a range close to the data of Misra and Bonilla.

An attempt to evaluate the effect of vapor velocity on the condensing mercury system was made by plotting $\frac{DG_m}{\mu} \frac{\rho_L}{\rho_v}$ against $\frac{h}{c_p G_m}(N_{Pr})^{0.5}$. The basis for this plot was the semi-emperical equation proposed by Carpenter and Colburn (2, p. 25) i.e. $\frac{h}{c_p G_m}(N_{Pr})^{0.5} = 0.065\sqrt{\frac{\rho_L}{\rho_v}\frac{f}{2}}$ ... (13)

in which they consider the effect of vapor velocity. Since the friction factor, f, is a function of the vapor Reynolds number, $\frac{DG_m}{\mu}$, this effect should be detectable by plotting $\frac{DG_m}{\mu} \frac{\rho_L}{\rho_v}$ versus $\frac{h}{c_p G_m}(N_{Pr})^{0.5}$. No definite trend was detected with the mercury data. With the present apparatus vapor flow is counter to the liquid flow and any increase in the vapor velocity should result in a reduction of the condensing coefficient.

Discussion and Analysis

Experimental condensing coefficients for mercury and mercury-sodium systems were 1% to 13% of the values predicted by the Nusselt equation. Similarly, for cadmium, the values are 0.45% to 11% of the theoretical values for filmwise condensation. The conditions that may be different from the conditions used in deriving the Nusselt equation are:

(1) Dropwise condensation

(2) Turbulent flow in the condensate film

(3) Ripples on the surface of the film

(4) Finite vapor velocity

All of these effects would contribute towards making the coefficient higher than predicted by the Nusselt equation except number (4) when the vapor flow is counter to the liquid flow. This situation existed in the experimental apparatus and could conceivably have brought about the low coefficients measured. An argument against this, however, is the fact that Misra and Bonilla (12, p. 11) made some measurements for condensation outside an inclined tube. They got low coefficients and vapor velocity here would have no effect.

Factors which might contribute to low coefficients a... also:

(1) Condensate hold-up and vapor hold-up in the condenser

(2) Plugging of the condenser from excess condensate

(3) Smaller effective heat transfer area than was assumed

(4) Radiation

(5) Error in measurement of the wall temperature

All of these factors are believed to have negligible effect except possibly (3) and (5). Equlibrium was attained quite easily so factor (1) and (2) are probably not significant. Loss of heat from the boiler by radiation is probably small because of the small area of the condenser compared to the boiler. The effective area of heat transfer could not be determined, but was probably well within 20% of that actually used in the calculation. There was considerable possibility for large error in measurement of the wall temperature due to uncertainty concerning the actual thermocouple position in the tube wall and conduction of heat along the thermocouple wires. It is improbable however that this error would be 10 to 100 fold.

Hence, it is probable that the low coefficients are due to factors associated with the condensation of liquid metals and connected with the type of apparatus used. Since the condensation could not be observed visually, an evaluation of these factors is not possible.

SUMMARY AND CONCLUSIONS

The condensing coefficients of mercury and mercury-sodium amalgams up to 1% sodium have been determined. It was found that the amalgams yielded no different results than the pure mercury. Values of the condensing coefficients ranged from 13% to 1% of the values predicted from the Nusselt relationship.

The condensing coefficients of cadmium were studied and the values obtained were from 11% to 0.45% of the values predicted from the Nusselt equation. Misra and Bonilla obtained condensing coefficients for sodium that were 15% to 5% of the predicted values; for mercury the values ranged from 20% to 6% of the theoretical values for air cooled condensers (12, p. 17).

A plot of $\frac{4\Gamma}{\mu}$ against $\frac{h}{k}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ showed considerable scattering of the data, but the data was in general agreement with the results of Misra and Bonilla.

Several factors have been considered to explain the general low results obtained in comparison to theoretical values. Although there was possibility for considerable experimental error in the measuring procedure this does not account for the magnitude of the disagreement. It would appear from present data that the condensing coefficients expected for a liquid metal vapor are lower than would be expected from the various theoretical relationships. Considerable work needs to be done particularly on the fluid mechanics of the system to gain fundamental information on the condensing process.

NOMENCLATURE

Symbol			Dimensions
1.	A	Area	ft.^{2}
2.	c_p	Heat capacity	Btu/lb.
3.	f	Friction factor	dimensionless
4.	G	Mass flow rate	lb./hr.ft.^{2}
5.	g	Acceleration of gravity	4.17 X 10^8 ft/hr^2
6.	g_c	Conversion factor	4.17 X 10^8 lb.(mass) ft./lb(force) hr^2
7.	H	Enthalpy	Btu/lb.
8.	h	Mean heat transfer coefficient	Btu/hr.ft.^{2} ^{o}F.
9.	k	Thermal conductivity	Btu/hr. ft.^{2} ^{o}F/ft.
10.	L	Length	ft.
11.	M	Molecular weight	lb./mole.
12.	mv	Millivolts	10-3 volts
13.	N_{Pr}	Prandtl number	dimensionless $c_p \mu/k$
14.	P	Pressure	lb./ft.^{2}
15.	q	Rate of heat flow	Btu/hr.
16.	R	Gas constant	
17.	r	Radius	ft.
18.	T	Absolute temperature	^{o}R
19.	t	Temperature	^{o}F
20.	X	Length of heat conduction path	ft.
21.	α	Condensation coefficient	dimensionless
22.	Γ	Mass flow rate based on periphery	lb./hr. ft.^{2}

Symbol		Dimensions
23. Δt	Temperature difference	^{o}F
24. λ	Latent heat of vaporization	Btu/lb.
25. μ	Viscosity	lb./hr. ft.
26. ν	Kinematic viscosity	ft.^{2}/hr.
27. π	Dimensionless group	
28. ρ	Density	lb./ft.^{2}
29. τ	Shear stress	lb./ft.^{2}
30. τ_v^*	Defined in equation (5)	Dimensionless

Subscripts

1.	f	Condensate film
2.	i	Interface
3.	L	Liquid
4.	m	Mean
4.	v	Vapor

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APPENDIX I

Experimental Data

Table II: Experimental data

Explanation

Thermocouple

I. Millivolt and temperature reading at thermocouple slot 4" from the condenser base.

II. Millivolt and temperature reading at thermocouple slot 8" from condenser base.

III. Millivolt and temperature reading at thermocouple slot $11\frac{1}{2}$" from condenser base.

IV. Millivolt and temperature reading of tower vapor thermocouple.

V. Millivolt and temperature reading of boiler vapor thermocouple.

VI. Millivolt reading of thermocouple in air space between guard heater and boiler shell.

EXPERIMENTAL DATA

TABLE II

Data For Water

Run	Thermocouples											Power Watts
	I		II		III		IV		V		VI	
	mv	°F	mv	°F	mv	°F	mv	°F	mv	°F	mv	
1	5.72	283.5	5.89	290.9	5.94	293.0	6.03	297.2	6.07	299.4	6.10	70
2	5.34	266.8	5.13	257.2	5.40	269.4	6.00	295.9	5.97	294.4	5.95	160
3	5.26	260.3	5.33	266.3	5.37	268.0	5.40	268.5	5.47	272.2	5.39	20
4	5.43	270.4	5.56	276.3	5.60	277.9	5.64	280.0	5.70	282.7	5.66	100
5	5.79	286.7	5.91	291.7	5.97	294.2	6.05	298.1	6.08	299.2	6.00	200
6	5.80	287.2	5.91	291.8	5.99	295.4	6.11	300.9	6.14	302.2	6.10	70
7	6.19	304.5	6.27	308.1	6.32	310.4	6.44	315.9	6.44	315.9	6.39	200
8	4.91	247.6	5.00	251.3	5.00	251.3	5.07	254.4	5.06	254.0	5.00	200
9	5.46	271.8	5.53	275.0	5.57	276.8	5.61	278.5	5.67	281.3	5.69	120
10	5.94	293.0	6.06	298.5	6.11	300.9	6.16	303.0	6.28	308.6	6.13	410
11	4.60	235.9	4.73	239.8	4.75	240.9	4.78	241.8	4.82	243.5	4.77	110
12	6.36	312.2	6.47	317.2	6.55	320.9	6.66	325.9	6.66	325.9	6.59	320
13	4.86	245.4	4.93	248.5	4.96	249.8	5.01	251.8	5.07	254.4	5.04	97.5

Data For Mercury

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
1	12.26	574.6	12.27	575.0	12.31	576.7	12.67	592.1	12.67	592.1	12.73	250
2	13.09	610.4	13.09	610.4	13.11	611.3	13.45	658.9	13.41	657.1	13.41	400
3	13.48	627.1	13.46	626.3	13.52	629.4	13.91	645.9	13.82	641.7	13.79	450
4	14.10	654.0	14.13	655.4	14.17	657.1	14.53	672.1	14.47	669.6	14.39	500
5	13.30	619.6	13.31	620.0	13.42	624.6	14.48	670.0	14.44	668.5	14.43	800
6	11.76	552.6	11.82	555.4	11.91	559.4	13.20	615.4	13.29	619.4	13.33	1,150

Data For Mercury Continued

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
7	13.7	614.0	13.20	615.4	13.22	616.3	13.70	636.3	13.67	635.0	13.64	700
8	13.64	634.0	13.70	636.3	13.74	638.1	14.11	654.5	14.10	654.0	14.07	200
9	13.97	648.6	14.05	651.7	14.06	652.2	14.53	672.2	14.51	671.3	14.53	650
10	13.21	616.7	13.21	616.7	13.27	618.5	13.86	643.5	13.91	645.9	13.99	700
11	12.65	591.3	12.70	596.3	12.78	597.1	13.15	613.0	13.16	613.5	13.13	500
12	14.15	656.3	14.21	658.9	14.23	659.6	14.66	677.6	14.64	676.7	14.59	500
13	13.97	648.4	14.06	652.1	14.10	654.3	14.34	664.3	14.36	665.0	14.38	650
14	12.74	595.4	12.80	598.0	12.81	598.5	13.39	623.5	13.47	626.7	13.41	900
15	11.81	555.0	11.97	561.7	11.91	559.4	12.92	603.0	12.89	601.7	12.91	1,500
16	14.20	658.5	14.24	660.0	14.23	659.6	14.44	668.5	14.47	669.6	14.49	600
17	13.11	611.3	13.15	613.0	13.21	615.9	13.51	628.5	13.48	627.1	13.47	500
18	14.03	650.9	14.04	651.3	14.07	652.6	14.33	663.9	14.39	666.3	14.38	850
19	13.38	623.0	13.40	624.4	13.46	626.3	13.65	634.4	13.66	634.9	13.69	700
20	14.24	660.0	14.25	660.4	14.29	662.6	14.63	676.3	14.61	675.4	14.65	800
21	12.10	563.0	12.14	565.0	12.16	565.9	12.52	585.9	12.51	585.4	12.55	1,000
22	13.01	607.1	13.06	609.1	13.10	610.9	13.26	618.0	13.27	618.4	13.29	350
23	13.29	619.4	13.33	620.9	13.41	624.4	13.63	633.5	13.74	638.0	13.71	500
24	13.85	643.0	13.93	646.7	13.99	649.4	14.45	668.9	14.47	669.6	14.41	550
25	13.67	635.0	13.71	636.7	13.79	640.4	14.00	649.4	14.05	651.3	14.07	300
26	13.22	616.3	13.26	618.0	13.34	621.3	13.63	633.5	13.70	636.3	13.75	650
27	14.01	650.0	14.07	652.6	14.05	651.7	14.45	669.4	14.47	669.7	14.50	400
28	12.93	603.4	12.98	605.9	13.03	608.0	13.28	619.4	13.31	620.0	13.36	850
29	12.39	580.0	12.46	583.0	12.53	586.3	14.20	658.5	14.27	661.3	14.23	700
30	12.50	585.0	12.59	588.9	12.76	596.3	14.34	664.4	14.38	665.9	14.40	1,000
31	12.57	588.0	12.63	589.6	12.70	593.5	14.46	669.4	14.47	669.6	14.40	800
32	12.71	593.9	12.79	598.6	12.86	600.4	14.51	671.3	14.54	672.6	14.59	850
33	12.84	599.6	12.91	602.6	12.97	605.4	14.56	673.5	14.58	673.9	14.63	950
34	12.67	592.1	12.73	595.0	12.80	598.0	14.47	669.4	14.51	671.3	14.55	1,100

Data For Mercury Continued

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
35	12.52	585.9	12.58	588.5	12.69	593.0	14.46	669.4	14.43	668.0	14.50	900
36	14.21	659.4	14.29	662.1	14.24	660.0	14.67	678.0	14.63	676.3	14.63	800
37	14.77	682.6	14.86	686.3	14.86	686.3	15.30	705.4	15.32	706.3	15.27	600
38	13.54	629.6	13.61	632.6	13.62	633.0	13.97	648.5	13.96	648.0	13.93	1,300
39	13.55	630.0	13.55	630.0	13.58	631.3	14.14	655.9	14.17	657.1	14.21	175
40	13.60	632.1	13.65	634.4	13.66	634.6	14.17	657.1	14.17	657.1	14.21	350
41	13.87	643.9	13.94	657.1	13.96	648.0	14.34	664.4	14.34	664.4	14.37	700
42	12.29	575.9	12.30	576.3	12.32	577.1	12.59	588.9	12.66	591.7	12.70	875
43	13.63	633.5	13.68	635.4	13.65	634.4	13.98	648.9	14.02	650.4	13.99	750
44	14.08	653.0	14.11	654.4	14.11	654.4	14.63	676.3	14.62	675.9	14.59	425
45	14.19	658.0	14.21	658.9	14.21	658.0	14.73	680.9	14.78	683.0	14.80	350
46	14.41	667.1	14.48	670.0	14.47	669.6	14.95	690.4	14.93	689.6	14.85	700
47	14.43	668.0	14.43	668.0	14.45	668.9	15.09	694.6	15.14	698.9	15.19	250

Data For Mercury+0.3% Sodium

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
1	12.95	604.6	12.95	604.6	12.97	605.4	13.44	625.4	13.44	625.4	13.39	1,050
2	14.50	670.9	14.54	672.6	14.56	673.5	15.01	693.0	15.04	694.4	15.04	700
3	14.89	686.3	14.87	686.7	14.99	692.1	15.74	724.4	15.76	725.0	15.72	550
4	12.59	588.5	12.62	590.0	12.61	589.6	13.08	610.0	13.09	610.4	13.10	850
5	12.88	601.3	12.90	602.4	12.92	603.0	13.35	631.7	13.39	623.5	13.39	900
6	14.39	666,3	14.46	669.4	14.46	669.4	15.01	693.0	15.07	695.4	15.08	900
7	14.57	673.9	14.59	674.6	14.61	675.4	15.03	693.9	15.05	694.6	15.01	150
8	14.27	661.3	14.30	662.6	14.30	662.6	14.90	688.0	14.95	690.4	14.90	650
9	11.72	550.9	11.75	552.1	11.72	552.6	12.20	571.7	12.25	573.9	12.26	600
10	12.13	578.9	12.13	578.9	12.14	579.4	12.76	596.3	12.75	595.9	12.79	300

Data For Mercury+0.3% Sodium Continued

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
11	12.44	582.1	12.42	581.3	12.46	583.0	13.00	606.7	13.06	609.4	13.09	400
12	13.13	612.1	13.16	613.5	13.16	613.5	13.69	635.9	13.72	637.1	13.69	900
13	13.65	634.4	13.71	636.7	13.71	636.7	14.38	665.9	14.38	665.9	14.36	800
14	11.70	550.0	11.71	550.4	11.74	551.7	12.27	575.0	12.25	573.9	12.24	500
15	11.22	528.9	11.27	530.9	11.26	530.4	11.69	547.6	11.72	550.9	11.73	600
16	12.10	567.6	12.13	568.9	12.13	568.9	12.62	590.0	12.66	591.7	12.68	400
17	11.80	554.6	11.85	556.7	11.85	556.7	12.31	576.7	12.34	578.0	12.38	700
18	12.40	580.4	12.42	581.3	12.42	581.3	12.96	605.0	12.97	605.4	12.97	400
19	12.89	601.7	12.93	603.5	12.94	603.9	13.42	624.6	13.44	625.4	13.42	550
20	13.45	625.9	13.45	625.9	13.46	626.3	13.99	649.4	13.98	648.9	13.98	900
21	13.21	615.9	13.21	615.9	13.22	616.2	13.73	637.6	13.77	639.4	13.75	800
22	13.37	622.6	13.42	624.6	13.42	624.6	14.05	651.7	14.05	651.7	14.03	150
23	14.01	650.0	14.03	650.9	14.02	650.4	14.71	680.0	14.74	681.3	14.75	500
24	14.69	678.9	14.77	682.6	14.79	683.5	15.44	711.3	15.49	713.5	15.44	1,000
25	11.03	520.4	11.03	520.4	11.06	521.3	11.50	541.3	11.54	543.0	11.56	650
26	11.51	541.7	11.58	545.0	11.58	545.0	12.65	591.3	12.69	593.0	12.70	700
27	12.87	600.9	12.89	601.7	12.93	603.5	13.97	648.0	13.97	648.0	13.89	1,100
28	13.72	637.1	13.75	638.5	13.76	638.9	14.44	668.5	14.48	670.0	14.42	100
29	15.01	693.0	15.05	694.6	15.06	695.0	15.66	720.9	15.66	720.9	15.64	900

Data For Mercury+1.0% Sodium

Run	I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
1	13.79	640.4	13.87	643.9	13.85	643.0	14.81	684.4	14.84	685.4	14.84	500
2	14.52	671.7	14.55	673.0	14.55	673.0	15.45	711.7	15.47	712.6	15.49	700
3	13.73	637.6	13.73	637.6	13.72	637.1	14.54	672.6	14.59	674.6	14.57	400

Data For Mercury+1.0% Sodium Continued

Run	Thermocouples I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
4	14.00	649.6	14.05	651.7	14.07	652.6	14.90	688.5	14.94	690.0	14.90	550
5	13.88	644.6	13.92	646.3	13.93	646.7	14.77	683.0	14.80	683.9	14.83	300
6	15.01	693.0	15.04	694.4	15.07	695.4	15.60	718.5	15.65	620.4	15.66	700
7	10.91	515.4	10.91	515.4	10.94	516.7	11.30	532.4	11.34	533.9	11.37	500
8	11.74	551.7	11.77	553.0	11.77	553.0	12.02	564.4	12.04	565.0	12.07	850
9	13.97	648.5	14.01	650.0	14.03	650.9	14.48	670.0	14.54	672.6	14.52	800
10	14.46	669.4	14.49	670.4	14.55	673.0	15.11	697.1	15.18	700.0	15.14	400
11	11.34	533.9	11.35	534.4	11.38	535.9	11.84	556.3	11.89	558.5	11.92	900
12	14.58	674.4	14.62	675.9	14.66	677.6	15.20	700.9	15.23	702.1	15.27	700
13	14.85	685.9	14.88	687.1	14.92	689.4	15.31	705.9	15.34	707.1	15.29	250
14	13.38	623.0	13.41	624.4	13.45	625.9	14.19	658.0	14.20	658.5	14.22	500
15	14.57	673.9	14.61	675.4	14.62	675.9	15.19	700.4	15.23	702.1	15.23	700
16	12.33	577.6	12.37	579.4	12.39	580.0	12.74	595.4	12.76	596.3	12.71	700
17	12.96	605.0	12.97	605.4	12.99	606.3	13.39	623.5	13.42	624.6	13.45	500
18	13.22	616.3	13.25	617.6	13.28	618.9	13.82	641.7	13.84	642.6	13.82	450
19	13.91	645.9	13.97	648.0	13.99	649.4	14.37	665.4	14.41	667.1	14.41	800
20	14.34	664.4	14.38	665.9	14.39	666.3	14.89	687.6	14.87	686.7	14.91	700
21	11.95	560.9	11.98	562.1	11.98	562.1	12.27	575.0	12.31	576.7	12.34	900
22	12.78	597.1	12.80	598.0	12.81	598.5	13.32	620.4	13.35	621.7	13.35	400
23	13.37	623.5	13.40	623.9	13.42	624.6	13.87	643.9	13.89	645.0	13.86	600
24	11.19	527.6	11.22	528.9	11.23	529.4	11.56	544.4	11.58	545.0	11.53	800
25	11.98	562.1	12.01	563.5	12.01	563.5	12.36	578.9	12.38	579.6	12.33	400
26	13.48	627.1	13.53	629.4	13.52	628.9	13.84	642.6	13.87	643.9	13.89	700
27	14.34	664.4	14.35	664.6	14.37	665.4	14.78	683.0	14.81	684.4	14.84	400
28	13.41	624.4	13.41	624.4	13.43	625.0	13.67	635.0	13.71	636.7	13.70	700
29	11.85	556.7	11.89	558.5	11.93	560.0	12.31	576.7	12.34	578.0	12.35	300
30	13.17	613.9	13.20	615.4	13.23	616.7	13.62	633.0	13.65	634.4	13.60	650

Data For Mercury+1.0% Sodium Continued

Run	Thermocouples											Power Watts
	I		II		III		IV		V		VI	
	mv	°F	mv	°F	mv	°F	mv	°F	mv	°F	mv	
31	14.49	670.4	14.53	672.1	14.56	673.5	15.00	692.6	15.05	694.6	15.07	300
32	14.92	689.9	14.97	691.3	14.99	692.1	15.34	707.1	15.33	706.7	15.30	900

Data For Cadmium

1	30.71	1,359.3	30.75	1,361.3	30.81	1,363.9	31.72	1,403.1	31.81	1,406.7	31.77	750
2	31.39	1,388.5	31.46	1,391.7	31.53	1,394.6	32.63	1,442.6	32.70	1,445.4	32.74	550
3	31.10	1,375.9	31.11	1,376.3	31.16	1,378.5	32.29	1,427.6	32.34	1,430.0	32.39	250
4	31.09	1,375.4	31.13	1,377.2	31.17	1,378.9	32.20	1,423.9	32.24	1,425.4	32.27	500
5	28.00	1,243.4	28.04	1,245.0	28.07	1,246.3	28.46	1,263.0	28.50	1,264.7	28.57	250
6	28.33	1,257.5	28.38	1,259.7	28.41	1,260.9	28.90	1,281.7	28.94	1,283.5	28.92	200
7	30.88	1,366.7	30.92	1,368.5	30.98	1,370.9	31.32	1,385.4	31.36	1,387.2	31.31	850
8	31.37	1,387.6	31.41	1,389.3	31.46	1,391.7	31.89	1,410.4	31.93	1,412.2	31.96	500
9	25.49	1,136.7	25.53	1,138.4	25.57	1,140.0	26.32	1,172.2	26.35	1,173.4	26.38	400
10	28.36	1,258.8	28.40	1,260.4	28.45	1,262.6	28.91	1,282.2	28.94	1,283.4	29.01	800
11	29.35	1,300.9	29.37	1,301.7	29.41	1,303.5	29.89	1,324.3	29.93	1,325.9	29.91	600
12	29.70	1,315.9	29.74	1,317.6	29.77	1,318.9	31.20	1,380.4	31.23	1,381.7	31.16	1,100
13	31.05	1,373.9	31.10	1,375.9	31.14	1,377.6	31.56	1,395.9	31.61	1,398.0	31.63	600
14	30.03	1,330.4	30.07	1,332.2	30.11	1,333.9	31.62	1,398.5	31.66	1,400.4	31.59	500
15	30.16	1,378.5	30.18	1,379.3	30.22	1,381.3	31.68	1,401.9	31.74	1,403.9	31.66	700
16	26.91	1,197.1	26.94	1,198.4	26.97	1,199.6	27.73	1,232.1	27.77	1,233.8	27.82	500
17	28.07	1,246.3	28.11	1,248.0	28.15	1,250.0	29.40	1,303.0	29.46	1,305.4	29.37	1,200
18	28.36	1,258.8	28.37	1,259.3	28.42	1,261.3	29.95	1,326.7	29.99	1,328.5	30.04	400
19	28.75	1,275.4	28.77	1,276.3	28.81	1,278.0	30.24	1,339.3	30.28	1,340.0	30.26	850
20	28.76	1,275.9	28.81	1,278.0	28.84	1,281.3	30.39	1,345.4	30.41	1,346.3	30.42	600
21	29.55	1,309.3	29.58	1,311.2	29.61	1,312.2	31.01	1,372.2	31.06	1,374.3	31.10	900

Data For Cadmium Continued

Run	Thermocouples I mv	I °F	II mv	II °F	III mv	III °F	IV mv	IV °F	V mv	V °F	VI mv	Power Watts
22	29.95	1,326.7	29.99	1,328.5	30.04	1,330.9	31.52	1,394.3	31.54	1,395.0	31.57	700
23	30.63	1,355.9	30.66	1,357.2	30.69	1,358.5	31.26	1,383.0	31.33	1,385.9	31.31	500
24	30.14	1,335.0	30.18	1,336.7	30.22	1,338.5	31.47	1,392.2	31.51	1,393.9	31.54	650
25	29.89	1,324.3	29.94	1,326.3	29.98	1,328.0	31.31	1,385.0	31.32	1,385.4	31.36	400
26	30.22	1,338.5	30.24	1,339.3	30.27	1,340.4	31.50	1,393.5	31.56	1,395.9	31.54	900
27	31.26	1,383.0	31.30	1,384.6	31.33	1,385.9	32.59	1,440.9	32.68	1,444.6	32.74	1,200
28	30.66	1,357.2	30.68	1,358.0	30.74	1,360.9	31.94	1,412.6	32.01	1,415.4	31.96	800
29	30.88	1,366.7	30.94	1,369.3	31.02	1,372.6	32.24	1,425.4	32.27	1,426.7	32.23	750
30	30.63	1,355.9	30.67	1,357.6	30.72	1,360.0	32.04	1,416.7	32.07	1,418.1	32.06	550
31	30.84	1,365.0	30.85	1,365.4	30.87	1,366.3	32.18	1,423.1	32.22	1,324.6	32.24	400
32	27.64	1,228.0	27.67	1,229.2	27.71	1,231.3	27.86	1,237.5	27.94	1,240.9	27.96	650
33	28.41	1,260.9	28.44	1,262.1	28.49	1,264.3	28.68	1,272.5	28.70	1,273.4	28.64	400
34	28.65	1,271.3	28.67	1,272.1	28.69	1,273.0	28.87	1,280.4	28.91	1,282.1	28.86	300
35	29.19	1,294.3	29.23	1,295.9	29.26	1,297.1	29.73	1,317.2	29.76	1,318.5	29.71	850
36	30.02	1,330.0	30.03	1,330.4	30.06	1,331.7	30.44	1,347.6	30.50	1,350.4	30.56	1,000
37	30.28	1,340.9	30.33	1,343.0	30.36	1,344.3	30.91	1,368.0	30.95	1,369.6	31.01	600
38	30.65	1,356.7	30.68	1,358.0	30.73	1,359.6	31.12	1,376.7	31.17	1,378.9	31.24	950
39	30.77	1,362.2	30.81	1,363.9	30.84	1,365.0	31.45	1,391.3	31.48	1,392.6	31.52	600
40	31.58	1,396.7	31.63	1,398.9	31.65	1,400.0	32.19	1,423.5	32.21	1,424.4	32.26	700

APPENDIX II

Calculated Data

Table III: Calculated Data

Explanation

Power:	Btu/hr
T_{vm}:	Mean vapor temperature, average of IV and V temperature readings
T_{som}:	Mean condenser outside surface temperature, average I, II, and III temperature readings.
T_{sim}:	Mean temperature of inside surface of condenser, using equation 6a and T_{som}.
Δt:	Difference of T_{vm} and T_{sim}.
Heat Flux:	Btu/hr ft^2, power/condenser heat transfer area.
h:	Btu/hr ft^2 °F/ heat flux/Δt.

CALCULATED DATA

TABLE III

Data For Water

Run	Power	T_{vm} °F.	T_{som} °F.	T_{sim} °F	Δt °F.	Heat Flux	h
1	239	298.3	263.7	285.0	13.3	2,890	217
2	546	296.7	264.5	267.1	29.6	6,600	237
3	68.2	270.4	264.9	265.2	5.2	824	129
4	341	281.4	274.9	276.5	4.9	4,110	841
5	682	298.7	290.9	294.1	4.6	8,240	1,790
6	239	301.6	291.4	292.7	8.9	2,890	325
7	682	312.9	307.8	311.0	1.9	8,240	4,340
8	682	254.2	250.0	253.2	1.0	8,240	8,250
9	409	279.9	274.4	276.3	3.6	4,950	1,380
10	1,400	305.8	297.6	304.2	1.6	16,900	10,600
11	375	242.7	238.9	240.7	2.0	4,540	2,270
12	1,090	325.9	316.8	322.0	3.9	13,200	3,380
13	332	253.1	247.9	249.1	4.0	4,010	1,000

Data For Mercury

Run	Power	T_{vm} °F.	T_{som} °F.	T_{sim} °F	Δt °F.	Heat Flux	h
1	853	592.1	575.4	578.8	13.3	10,030	779
2	1,370	658.0	610.8	616.3	41.7	16,600	398
3	1,540	643.8	627.6	633.8	10.0	18,600	1,860
4	1,710	670.8	655.5	662.3	8.5	20,500	2,430
5	1,730	669.2	621.1	632.1	37.1	21,000	894
6	3,920	617.4	555.8	571.5	45.9	47,500	1,032
7	2,390	636.9	615.2	624.8	12.1	28,900	2,390
8	683	654.2	636.1	638.8	15.4	8,260	537
9	2,220	671.8	651.1	660.0	11.8	26,800	2,270
10	2,390	644.7	617.3	626.9	17.8	28,900	1,620
11	1,710	613.2	594.9	601.7	11.5	20,500	1,800
12	1,710	677.1	658.3	665.1	12.0	20,500	1,720
13	2,220	664.6	651.6	660.5	4.1	26,800	6,540
14	3,070	625.1	597.3	509.6	15.5	37,200	2,400
15	5,120	602.4	558.6	679.1	23.3	61,900	2,660
16	2,050	669.0	659.4	667.6	1.4	25,100	17,500
17	1,710	627.8	613.4	620.2	7.6	20,500	2,730
18	2,900	665.1	651.6	663.2	1.9	35,100	18,400
19	2,390	634.65	624.5	634.1	0.55	28,900	52,600
20	2,730	675.9	661.0	672.0	3.9	33,000	8,490
21	3,410	585.6	564.6	578.3	7.4	41,300	5,610
22	1,190	618.2	609.0	613.8	6.4	14,400	2,260

Data For Mercury Continued

Run	Power	T_{vm} °F	T_{som} °F	T_{sim} °F	Δt °F	Heat Flux	h
23	1,710	635.8	621.6	628.4	7.2	20,500	2,870
24	1,880	669.4	646.4	653.9	15.5	22,800	1,460
25	1,020	650.4	637.4	641.5	8.9	12,300	1,390
26	2,220	634.9	618.5	627.4	7.5	26,800	3,580
27	1,360	669.6	651.4	656.9	12.7	16,500	1,300
28	2,900	619.7	605.8	617.4	2.3	35,100	15,300
29	2,390	659.9	583.1	592.7	67.2	28,900	430*
30	3,410	665.2	590.1	603.8	61.4	41,300	672*
31	2,730	669.5	590.4	601.3	68.2	33,000	484*
32	2,900	672.0	597.6	609.2	62.8	35,100	558*
33	3,300	673.7	602.5	615.7	58.0	40,000	688*
34	3,750	670.4	595.0	610.0	60.4	45,400	751*
35	3,070	668.7	589.8	602.1	66.6	37,200	558*
36	2,730	677.2	660.5	671.5	5.7	33,000	5,800*
37	2,050	706.0	685.7	688.1	17.9	24,800	1,380*
38	4,430	648.3	631.7	636.9	11.4	53,600	4,700*
39	597	656.5	630.5	637.5	19.0	7,220	380
40	1,190	657.1	633.7	635.1	22.0	14,400	657
41	2,390	664.4	646.3	649.1	15.3	28,900	1,890
42	2,980	590.3	576.4	588.2	2.1	36,100	17,200
43	2,560	649.4	634.4	644.7	4.7	31,000	6,590
44	1,450	676.2	653.9	659.7	16.5	18,000	1,060
45	1,190	682.0	658.6	663.4	18.6	14,400	777
46	2,390	690.0	666.4	676.0	14.0	28,900	2,060
47	853	696.3	668.3	671.7	24.6	10,300	430

Data For Mercury 0.3% Sodium

1	3,580	625.4	604.3	619.2	6.2	43,300	6,990
2	2,390	693.6	672.3	681.9	11.7	28,900	2,470
3	1,880	724.7	688.4	695.9	28.8	22,700	788
4	2,900	610.2	594.0	605.6	4.6	35,100	4,630
5	3,070	622.6	602.2	614.5	8.1	37,100	4,580
6	3,070	694.2	668.4	680.7	13.5	37,100	2,750
7	5,120	694.2	674.7	676.7	17.5	6,190	354*
8	2,220	689.2	662.2	671.1	18.1	26,800	1,480
9	2.050	572.8	551.9	560.1	12.7	24,800	1,950

* Poor results due to the use of a blower for heat removal. These data were not plotted or used in the various analyses.

Data For Mercury 0.3% Sodium Continued

Run	Power	T_{vm} °F	T_{som} °F	T_{sim} °F	Δt °F	Heat Flux	h
10	1,020	596.1	579.1	583.2	12.9	12,500	968
11	1,360	608.0	582.1	587.6	20.4	16,500	794
12	3,070	636.5	613.0	625.3	11.2	37,100	3,320
13	2,730	665.9	635.9	646.8	19.1	33,000	1,730
14	1,700	574.5	550.7	557.5	17.0	20,600	1,210
15	2,050	548.0	530.0	538.2	9.8	24,800	2,530
16	1,360	590.8	568.5	574.0	16.8	16,500	982
17	2,390	577.4	556.0	565.6	11.8	28,900	2,450
18	1,360	605.2	581.0	586.5	18.7	16,500	883
19	1,880	625.0	603.0	610.5	14.5	22,700	1,560
20	3,070	649.2	626.0	638.3	10.9	37,100	3,410
21	2,730	638.5	616.0	626.9	11.6	33,000	2,850
22	512	651.7	623.9	625.9	25.8	6,190	240*
23	1,700	680.7	650.4	657.2	23.5	20,600	878
24	3,410	712.4	681.7	695.4	17.0	41,300	2,430
25	2,220	542.2	520.7	529.6	12.6	26,800	2,130
26	2,390	592.2	543.9	553.4	38.8	28,900	744
27	3,750	648.0	602.0	617.0	31.0	45,400	1,460
28	341	667.8	638.1	639.5	28.3	4,130	146*
29	3,070	720.9	694.2	706.5	14.4	37,100	2,580

Data For Mercury 1.0% Sodium

Run	Power	T_{vm} °F	T_{som} °F	T_{sim} °F	Δt °F	Heat Flux	h
1	1,700	685.1	642.4	649.2	35.9	20,600	575
2	2,390	712.2	672.6	682.2	40.0	28,900	722
3	1,360	673.6	637.4	642.9	30.7	16,500	538
4	1,880	689.2	651.1	658.6	30.6	22,800	742
5	1,020	683.4	645.9	650.0	33.4	12,400	371
6	2,390	719.4	694.3	703.9	15.5	28,900	1,860
7	1,700	533.2	515.8	522.6	10.6	20,600	1,950
8	2,900	564.7	552.6	564.2	0.5	34,400	69,000
9	2,730	671.3	649.8	660.7	10.6	33,000	3,110
10	1,360	698.5	670.9	676.4	22.1	16,500	747
11	3,070	557.4	534.7	647.0	10.4	37,100	3,570
12	2,390	701.5	676.3	685.9	15.6	28,900	1,850
13	852	706.5	687.5	690.9	15.6	10,300	661
14	1,700	658.2	624.4	631.2	27.0	20,600	764
15	2,390	701.2	675.1	684.7	16.5	28,900	1,750
16	2,390	595.8	579.0	588.6	7.2	28,900	4,010
17	1,700	624.0	605.6	612.4	11.6	20,600	1,780

* Low heat fluxes. These data were not plotted or included in the various analyses.

Data For Merury 1.0% Sodium

Run	Power	T_{vm} °F	T_{som} °F	T_{sim} °F	Δt °F	Heat Flux	h
18	1,530	642.1	617.6	623.1	19.0	16,500	869
19	2,730	66.2	648.1	659.0	7.2	33,000	4,580
20	2,390	687.2	665.5	675.1	12.1	28,900	2,390
21	3,070	575.8	561.7	574.0	1.8	37,100	20,600
22	1,360	621.0	597.9	603.4	17.6	16,500	938
23	2,050	644.4	624.0	632.2	12.2	24,800	2,030
24	2,730	544.7	528.6	539.5	5.2	33,000	6,350
25	1,360	579.2	563.0	568.5	10.7	16,500	1,540
26	2,390	642.2	628.5	638.1	4.1	28,900	7,040
27	1,360	683.7	664.8	670.3	13.4	16,500	1,230
28	2,390	635.8	624.6	634.2	1.6	28,900	18,000
29	1,020	577.4	558.4	562.5	14.9	12,400	831
30	2,220	633.7	615.4	624.3	9.4	26,800	2,850
31	1,020	693.6	672.0	676.1	17.5	12,400	707
32	3,070	704.6	691.1	603.4	1.2	37,100	31,000

Data For Cadmium

1	2,560	1,404.9	1,361.3	1,370.7	34.2	31,000	906
2	1,880	1,444.0	1,391.6	1,398.5	45.5	22,700	500
3	850	1,428.8	1,376.9	1,380.0	48.8	10,300	211
4	1,700	1,424.6	1,377.2	1,383.5	41.1	20,600	501
5	850	1,263.8	1,244.9	1,248.0	15.8	10,300	652
6	682	1,282.6	1,259.6	1,267.1	15.5	8,230	531
7	2,860	1,386.3	1,368.7	1,379.4	6.9	34,600	5,010
8	1,700	1,411.3	1,389.5	1,395.8	15.5	20,600	1,330
9	1,360	1,172.8	1,138.4	1,143.4	29.4	16,500	561
10	2,730	1,282.8	1,259.3	1,269.3	13.5	33,000	2,440
11	2,050	1,325.1	1,302.0	1,309.5	15.6	24,800	1,590
12	3,750	1,381.0	1,317.5	1,321.3	69.7	45,400	651
13	2,050	1,397.0	1,375.8	1,383.3	13.7	24,800	2,810
14	1,700	1,399.4	1,332.2	1,338.5	60.9	20,600	339
15	2,390	1,402.6	1,379.7	1,388.5	14.1	28,900	2,050
16	1,700	1,233.0	1,198.4	1,204.7	28.3	20,600	728
17	4,090	1,304.2	1,248.1	1,263.2	41.0	49,500	1,210
18	1,360	1,327.6	1,249.5	1,254.5	73.1	16,500	226
19	2,860	1,340.1	1,276.6	1,287.3	52.8	34,600	655
20	2,050	1,345.8	1,278.3	1,285.8	60.0	24,800	413
21	3,070	1,373.2	1,310.9	1,322.2	51.0	37,100	728
22	2,390	1,394.6	1,328.7	1,337.5	57.1	28,900	506
23	1,700	1,384.5	1,357.3	1,363.6	20.9	20,600	986
24	2,220	1,393.0	1,336.7	1,344.9	48.1	26,900	559

Data For Cadmium Continued

Run	Power	T_{vm} °F	T_{som} °F	T_{sim} °F	Δt °F	Heat Flux	h
25	1,360	1,385.2	1,326.3	1,331.3	53.9	16,500	306
26	3,070	1,394.7	1,339.4	1,350.7	44.0	37,100	843
27	4,090	1,442.0	1,384.5	1,399.6	42.4	49,500	1,170
28	2,730	1,414.0	1,358.7	1,368.7	45.3	33,000	728
29	2,560	1,426.0	1,369.5	1,378.9	47.1	31,000	658
30	1,880	1,417.4	1,357.8	1,364.7	52.7	22,700	431
31	1,360	1,423.8	1,365.6	1,370.6	53.2	16,500	310
32	2,200	1,239.2	1,229.2	1,237.4	1.8	22,600	12,600
33	1,360	1,273.0	1,262.4	1,267.4	5.6	16,500	2,950
34	1,020	1,281.2	1,272.1	1,275.9	5.3	12,400	2,340
35	2,860	1,317.8	1,295.8	1,306.5	11.3	34,600	3,070
36	3,410	1,349.0	1,330.7	1,343.3	5.7	41,300	7,250
37	2,050	1,368.8	1,342.7	1,350.2	18.6	24,800	1,330
38	3,240	1,377.8	1,358.1	1,370.0	7.8	39,200	5,030
39	2,050	1,392.0	1,363.7	1,371.2	20.8	24,800	1,190
40	2,390	1,424.0	1,398.5	1,407.3	16.7	28,900	1,730

APPENDIX III

Physical Data for Metals

PHYSICAL DATA FOR METALS

PHYSICAL DATA FOR STAINLESS STEEL (304)

Thermal Conductivity (13, p. 456)

$\frac{Btu - ft}{hr\ ft^2\ ^oF}$	^oF
9.4	212
12.4	932
12.1	1,400 (16, p. 314)
15.0	1,400 (5, p. 184)

PHYSICAL DATA FOR CADMIUM

Viscosity (9, p. 41)

Centipoises	T^oC
2.37	350
2.16	400
1.84	500
1.54	600

Thermal Conductivity (9, p. 41)

$\frac{Cal}{sec-cm-^oC}$	^oC
0.106	355
0.105	358
0.105	380
0.119	435

Density (9, p. 40)

g/cm^3	^oC
8.01	330
7.99	350
7.93	400
7.82	500
7.72	600
7.51	1382^oF (16, p. 1134)

Latent Heat of Vaporization (13, p. 210)

Cal/mole
23,870

Vapor Pressure (9, p. 40)

mm Hg	^oC
1	394
10	484
100	611
200	658
400	711
760	$1,409^oF$

Heat Capacity (9, p. 41)

$Cal/g-^oC$	^oC
0.0632	321 to 700
0.077	321 (4, p. 2085)

PHYSICAL DATA FOR MERCURY

Viscosity (9, p. 43)

Centipoises	°C
1.85	-20
1.68	0
1.55	20
1.21	100
1.01	200
0.921	340 (4, p. 1997)

Thermal Conductivity (9, p. 43)

cal/sec-cm-°C	°C
0.0196	0
0.0231	60
0.0261	120
0.0279	160
0.0303	220

Density (9, p. 42)

g/cm^3	°C
13.645	-20
13.546	20
13.352	100
13.115	200
12.881	300
12.74	360 (4, p. 1955)

Latent Heat of Vaporization (13, p. 210)

Cal/mole
13,980

Vapor Pressure (9, p. 42)

mm Hg	°C
1	126.2
10	184.0
100	261.7
200	290.7
400	323.0
760	675 °F

Heat Capacity (9, p. 43)

cal/g-°C	°C
0.03334	0
0.03279	100
0.03245	200
0.03234	300
0.03256	450

APPENDIX IV

Sample Calculations

SAMPLE CALCULATIONS

1. Calculation of t_{sim} using equation (6a)

$$t_1 = t_{sim} \quad \frac{q\Delta X}{2\pi \ r_{lnm} \ L \ k} + t_2$$

$t_2 = t_{som}$;

$$r_{lnm} = \frac{(0.25-0.012) - (0.25-0.065)}{\ln \dfrac{0.25-0.012}{(0.25-0.065)}} \text{ in}$$

$$r_{lnm} = \frac{0.053 \text{ in.}}{0.251 \ \dfrac{12 \text{ in.}}{\text{ft.}}} = 0.0176 \text{ ft.}$$

$L_{condenser} = 10.25$ in.

Consider cadmium run no. 1

Best available data at 1400 °F. for cadmium

$$\text{Viscosity} = 3.72 \ \frac{\text{lb.}}{\text{ft. hr.}} = 1.54 \text{ centipoise}$$

$$\text{Thermal Conductivity} = \frac{28.8 \text{ Btu}}{\text{hr. ft. } ^{\circ}\text{F}}$$

$$\text{Heat of Vaporization} = 212 \ \frac{\text{cal}}{\text{gram}} = 381 \ \frac{\text{Btu}}{\text{lb.}}$$

$$\text{Density} = 469 \ \frac{\text{lb.}}{\text{ft.}^3}$$

$$\text{Heat Capacity} = 0.0632 \ \frac{\text{Btu}}{\text{16 } ^{\circ}\text{F.}}$$

Thermal Conductivity of stainless steel (304)

$$= 12.6 \ \frac{\text{Btu}}{\text{hr.ft. } ^{\circ}\text{F.}}$$

$$t_{sim} = \frac{750 \text{ watts } (0.053) \text{ in. } (3.41) \frac{\text{Btu}}{\text{hr. watt}} \frac{12 \text{ in.}}{\text{ft.}}}{2\pi\ (0.0176 \text{ ft.})\ 12 \frac{\text{in}}{\text{ft}}\ (10.25) \text{ in. } 12.6 \frac{\text{Btu}}{\text{hr.ft.}^{\circ}\text{F.}}}$$

$+ 1361.3\ ^{\circ}\text{F.}$

$= 9.4\ ^{\circ}\text{F.} + 1361.3\ ^{\circ}\text{F.} = 1370.7\ ^{\circ}\text{F.}$

2. Calculation of h using equation (8)

$$h = \frac{q}{\Delta t\ A}$$

cadmium run no. 1

$\Delta t = t_{vm} - t_{sim} = 34.2\ ^{\circ}\text{F.}$

$A_{condenser} = 0.0826 \text{ ft.}^2$

$$h = \frac{750 \text{ watts } (3.41) \frac{\text{Btu}}{\text{hr. watt}}}{34.2\ ^{\circ}\text{F.}\ (0.0826) \text{ ft.}^2} = 906 \frac{\text{Btu}}{\text{hr. ft.}^2\ ^{\circ}\text{F.}}$$

$$\text{heat flux} = \frac{750 \text{ watts } (3.41) \frac{\text{Btu}}{\text{hr. watt}}}{0.0826 \text{ ft.}^2} = 31{,}000 \frac{\text{Btu}}{\text{hr. ft.}^2}$$

3. Calculation of $\frac{4\Gamma}{\mu}$ and $\frac{h}{K}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$ at 1400 °F.

cadmium run no. 1

$$\frac{4\Gamma}{\mu} = \frac{\text{Power}}{\lambda\,(\text{Perimeter})\ \mu}$$

$$= \frac{(4) 750 \text{ watts } (3.41) \frac{\text{Btu}}{\text{hr.watt}}\ 12 \frac{\text{in}}{\text{ft}}}{212 \frac{\text{cal}}{\text{g}}\ 1.8 \frac{\text{Btu g}}{\text{lb cal}}\ 1.54 \text{ centipoise} \frac{(2.42) \text{ lb}}{\text{ft hr centipoise}} (2)(\pi) 0.185 \text{ in}}$$

$= 74.6$

$$\frac{h}{k}\left(\frac{\nu^2}{g}\right) = \frac{906 \frac{\text{Btu}}{\text{hr ft}^2\ {}^{\circ}\text{F.}}}{28.8 \frac{\text{Btu}}{\text{hr ft}\ {}^{\circ}\text{F}}} \left[\left(\frac{(0.00794)^2\ \text{ft}^4}{\text{hr}^2\ 4.17 \times 10^8\ \frac{\text{ft}}{\text{hr}^2}}\right)\right]^{\frac{1}{3}} = 0.00168$$

4. Calculation of h from the Nusselt equation, equation (1) cadmium at 1400 °F.

$$h = 0.943 \left(\frac{k^3 \rho^2 g \lambda}{L \mu \Delta t}\right)^{\frac{1}{4}}$$

$$h = 0.943 \left[\frac{(28.8)^3 \frac{\text{Btu}^3}{\text{hr}^3\ {}^{\circ}\text{F}^3\ \text{ft}^3} \frac{(469)^2 \text{lb}^2}{\text{ft}^6} 4.17\text{X}10^8 \frac{\text{ft}}{\text{hr}^2} 381 \frac{\text{Btu}}{\text{lb}}}{3.72 \frac{\text{lb}}{\text{ft hr}}\quad 0.855 \text{ ft}\quad \Delta t}\right]^{\frac{1}{4}}$$

take a Δt of 100 °F.

$$h = 0.943 \left(2.63 \times 10^{20} \frac{\text{Btu}^4}{\text{hr}^4\ \text{ft}^8\ {}^{\circ}\text{F}^3}\right)^{\frac{1}{4}} \left(\frac{1}{100\ {}^{\circ}\text{F}}\right)^{\frac{1}{4}} = 38{,}000 \frac{\text{Btu}}{\text{hr ft}^2\ {}^{\circ}\text{F}}$$

5. Calculation of the Prandtl number at 1400 °F.

$$N_{Pr} = \frac{\mu c_p}{k} = \frac{3.72 \frac{\text{lb}}{\text{ft hr}} (0.0632) \frac{\text{Btu}}{\text{lb}\ {}^{\circ}\text{F}}}{28.8 \frac{\text{Btu}}{\text{hr ft}\ {}^{\circ}\text{F}}} = 0.00819$$