FILM COEFFICIENT OF HEAT TRANSFER OF FREON-12 CONDENSING INSIDE A SINGLE HORIZONTAL TUBE

by

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INTRODUCTION

In practice, horizontal vapor-in-tube condensers are preferable to vertical tube condensers. The main reason for this is that tube bundles from the vertical tube condensers cannot be pulled for cleaning as easily as horizontal tubes. However, very little data exist on film coefficients for condensing vapors inside horizontal tubes. Since Freon-12 is widely used in the refrigeration industry and since there is a lack of information on the characteristic of condensing Freon-12 inside horizontal tubes, a cooperative research project between the American Society of Refrigerating Engineers and the Engineering Experiment Station at Kansas State College was established to investigate the condensation of Freon-12 in horizontal tubes.

Many investigators have compared their data with those predicted by Nusselt's equation. Most of the experiments were on the vertical tubes and the outside of horizontal tubes. An interesting experimental investigation of the condensation of Freon-12 on the outside surface of a bank of horizontal tubes was carried out by Young and Wohlenberg (12), P. 787. The result of this investigation, as to film coefficient, was correlated with Nusselt's number for condensation and reasonably good agreement was found with the results deduced from Nusselt's theory of condensation in so far as trends are concerned.

In 1929, Jacob (6), P. 683, and Spencer (10) in 1950, investigated the steam coefficient of heat transfer inside a horizontal tube. They both concluded that the film coefficient varies with the length and periphery of the condensing tube. Jacob found that with a tube in a horizontal position, much higher rates of heat transfer were obtained than were obtained with the tube in a vertical position. He found the distribution of velocity and the film thickness around the periphery as shown in Plate I. Spencer developed the following empirical equation to fit the experimental data.

$$\frac{h_f}{\phi} = (0.0887 + 3.154 \times 10^{-6}\ G_{av})\left(\frac{4\Gamma}{\mu_f}\right)^{0.1412} \qquad (1)$$

Spencer also concluded that the increase in film coefficient with the increase in heat transfer rate due to the turbulence in the film was caused by steam velocity.

Brewster (2) in 1951, investigated the effects of vapor velocity on the film coefficient of heat transfer of vapors condensing inside a horizontal tube. He obtained the following correlation to fit the experimental data.

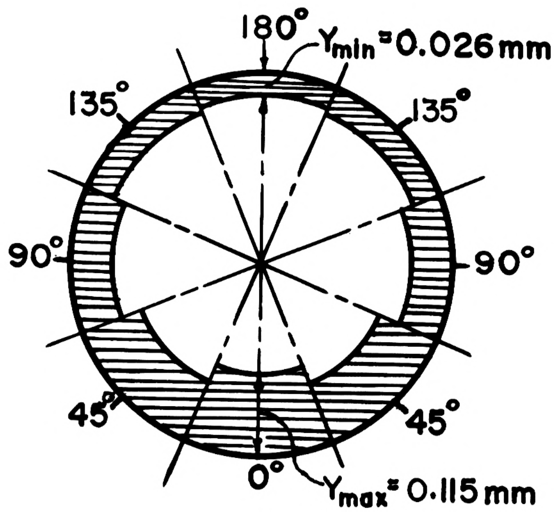
$$h_f = 7.91 \times 10^{-4}\left[\frac{D^{3.3} G\, \rho_f\, \lambda\, g^{0.5}}{k_f\, \Delta t_c\, \mu_v}\right]^{0.8} \qquad (2)$$

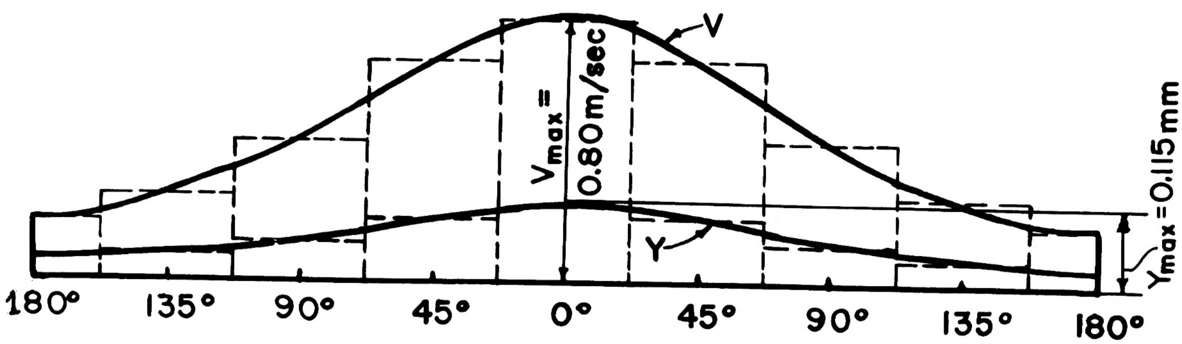
He concluded that the film coefficient of heat transfer increases with an increase in vapor velocity due to an apparent increase in the turbulence of the condensing film and also varies proportionally with the reciprocal of the temperature drop through the condensing film.

PLATE I

Thickness and velocity of water film inside a horizontal tube in which flowing saturated steam is condensed.

PLATE I


180°
Y_{min}=0.026 mm
135°
135°
90°
90°
45°
45°
0°
Y_{max}= 0.115 mm


V
V_{max}= 0.80 m/sec
Y
Y_{max}=0.115 mm
180°
135°
90°
45°
0°
45°
90°
135°
180°

THEORETICAL ANALYSIS

There are three modes of heat transmission, known as heat conduction, heat convection, and heat radiation. The three fundamental laws are as follows:

$$\frac{dQ}{d\theta} = -kA \frac{dt}{dL} \qquad (3)$$

where $dQ/d\theta$ = the rate of flow of heat, B/hr

A = the area at right angles to the direction in which heat flows, ft^2

dt/dL = the rate of change of temperature with distance in the direction of the flow of heat, i.e., the temperature gradient, °F/ft

k = the thermal conductivity, B/hr-ft °F

For steady flow of heat, $dQ/d\theta$ is constant and may be replaced by q, the heat transferred in B/hr.

For heat convection, Newton's law of cooling is

$$\frac{dQ}{d\theta} = h\,A\,\Delta t \qquad (4)$$

where h = the coefficient of heat transfer, B/hr-ft^2 °F.

For perfect black body heat radiation, Stefan-Boltzmann's law is

$$\frac{dQ}{d\theta} = \sigma\,A\,T^4 \qquad (5)$$

where σ = the Stefan-Boltzmann dimensional constant, energy/(area)(time)(deg abs)^4.

T = the absolute temperature of the surface, °R

When heat transmission occurs between a solid surface and a fluid, both conduction and convection are involved. Heat transfer between solid walls and a fluid is governed only by the laws of the flow of fluids and heat conduction (6), P. 16. The heat is transferred by convection from the main body of the fluid to the stagnant film of fluid and it must flow through the film by conduction. Because of the impracticability of measuring the thickness of the film and the interdependence of heat conduction and convection, it is necessary to define the film coefficient h_f by the following equation:

$$q = h_f A \Delta t \qquad (6)$$

where q = the rate of heat transfer, B/hr

The subject of heat transfer from condensing vapors to solid surfaces has not received as much attention as that from a solid surface to a non-boiling liquid. This is due to the experimental and theoretical difficulties. There are two modes of condensation, dropwise condensation and film condensation. Generally, film condensation occurs on wettable surfaces. Dropwise condensation is more effective than film condensation. Film condensation is easy to establish and remains much more stable in operation.

In 1916, Nusselt (Monrad and Badger, 9), P. 1103, in his mathematical treatment of vapor condensation, studied the quantitative effects of physical properties of the vapor and liquid, the effects of impurities, and the effects of the superheat and velocity of the vapor and the size and shape of the surface on the transmission of heat from condensing vapors.

Nusselt considered the following five cases:

1. Vapor condensing on a smooth, plane surface, making the angle ϕ with the horizontal.
2. Vapor condensing on the outside of a horizontal tube.
3. Vapor condensing on the surface as in (1) but with appreciable vapor velocity.
4. Superheated vapor condensing on any surface.
5. Impure vapor condensing on any surface.

In order to simplify the mathematical treatment, Nusselt made the following assumptions.

1. The film of condensate is so thin that the temperature gradient through it is a straight line.
2. The heat is all carried to the metal surface by pure conduction in the direction perpendicular to the surface.
3. Physical properties of the condensate may be taken at the mean film temperature.
4. The surface is relatively clean and smooth.
5. The film of condensate always moves in viscous motion.
6. The curvature of the film may be neglected.
7. The temperature of the solid surface is constant.

In 1916, Nusselt derived theoretical relations for predicting the coefficient of heat transfer between a pure saturated vapor and a colder surface. He developed the equation for film-type condensation on flat vertical surfaces and the exterior surfaces of vertical and horizontal pipe. He obtained the following dimensionless equation:

$$h_m \left[\frac{\mu_f^2}{k_f^3 \rho_f^2 g} \right]^{1/3} = a \left[\frac{4 \Gamma}{\mu_f} \right]^{-1/3} \qquad (7)$$

where h_m = mean value of h with respect to height of condensing surface, $B/hr\text{-}ft^2\ {}^\circ F$

μ_f = absolute viscosity of condensate film, lb/hr-ft

k_f = thermal conductivity of condensate film, B/hr-ft °F

ρ_f = density of condensate film, lb/ft^3

g = acceleration due to gravity, ft/hr^2

Γ = mass rate of flow of condensate from lowest point on condensing surface, divided by the breadth, lb/hr-ft; for horizontal tube with condensing vapor inside tube $\Gamma = \frac{W}{\pi D}$, where D is the inside diameter of the pipe.

In this equation, all properties must be expressed in consistent units. The lb-ft-hr-°F system was used in this paper. For a fluid condensing on the outside of tubes, the value of the constant "a" in the equation 7 is 1.47 for vertical surfaces (McAdams, 8), P. 330, and 1.51 for a single horizontal pipe (8), P. 338.

Application of Nusselt's theory to data for vapor condensation on the outside of horizontal tubes shows that the theory is valid for this case, and its application to data on vertical tubes with condensation on the outside surfaces shows that on long tubes or at high temperature differences, the theory does not hold, probably owing to the turbulence and drop formation (Monrad and Badger, 9), P. 1103. Thus for the outside surface of horizontal tubes, it appears that the assumptions made by Nusselt are quite well fulfilled under ordinary conditions in practice. For this case, if the physical properties of vapors are known, the coefficient of heat transfer may be calculated for any vapor with accuracy of 10 per cent (5), P. 1109.

In case of the condensation of vapor on inside surface of horizontal tubes of small diameter, the gravitational force is negligible. Dimensional analysis of the factors affecting the film coefficient of heat transfer, h_f, gives the following relation.

$$\frac{h_f D}{k_b} = C \left[\frac{DG}{\mu_b}\right]^n \left[\frac{C_p \mu_b}{k_b}\right]^m \qquad (8)$$

where the constants c, n, and m are to be determined experimentally. All physical properties are to be evaluated at bulk temperature. If the tube length is important, as with short tubes, the ratio L/D must be included in the above equation 8.

In this investigation of the condensation of Freon-12 inside a horizontal tube, the value of the Prandtl number, $\frac{C_p \mu_b}{k_b}$, was found to be nearly constant, so the following dimensionless relation was used for correlation of the experimental data:

$$\frac{h_f D}{k_b} = C \left[\frac{DG}{\mu_b}\right]^n \qquad (9)$$

DESIGN AND CONSTRUCTION OF APPARATUS

To accurately determine the film coefficient of heat transfer requires close control of the experimental conditions and accurate measurements of several values, such as vapor temperature, condensing surface temperature, and the quantity of heat transfer, so particular attention was given to these measurements.

A photograph and a schematic diagram of the test apparatus are shown in Plate II and Plate III, respectively. The system consisted of several parts such as boiler, superheater, horizontal condenser, vertical condenser, flow meter, pressure gages, immersion heater, potentiometer, pressure control, etc. The design of this apparatus was based on the design data given in Appendix B. A photograph of the principal components of the test apparatus is shown in Plate IV.

A sectional view of the test section in the horizontal condenser is shown in Plate V. The test condenser consisted of a 1/2-inch inside diameter brass pipe jacketed by a 13/16-inch inside diameter brass pipe. Maximum allowable working stress for brass up to 150 degrees F is 5000 psi (which is very high, considering the possible conditions of this experiment). The inside diameter of the inner condenser pipe was established by considering that a relatively high vapor velocity would be desirable. At the same time it was considered that inside diameter should not be so small that measurements of temperature would be difficult, or possibly introduce a variable in the system, which

PLATE II

Photograph of the test apparatus for studying the condensation of Freon-12 inside a single horizontal tube.

PLATE II

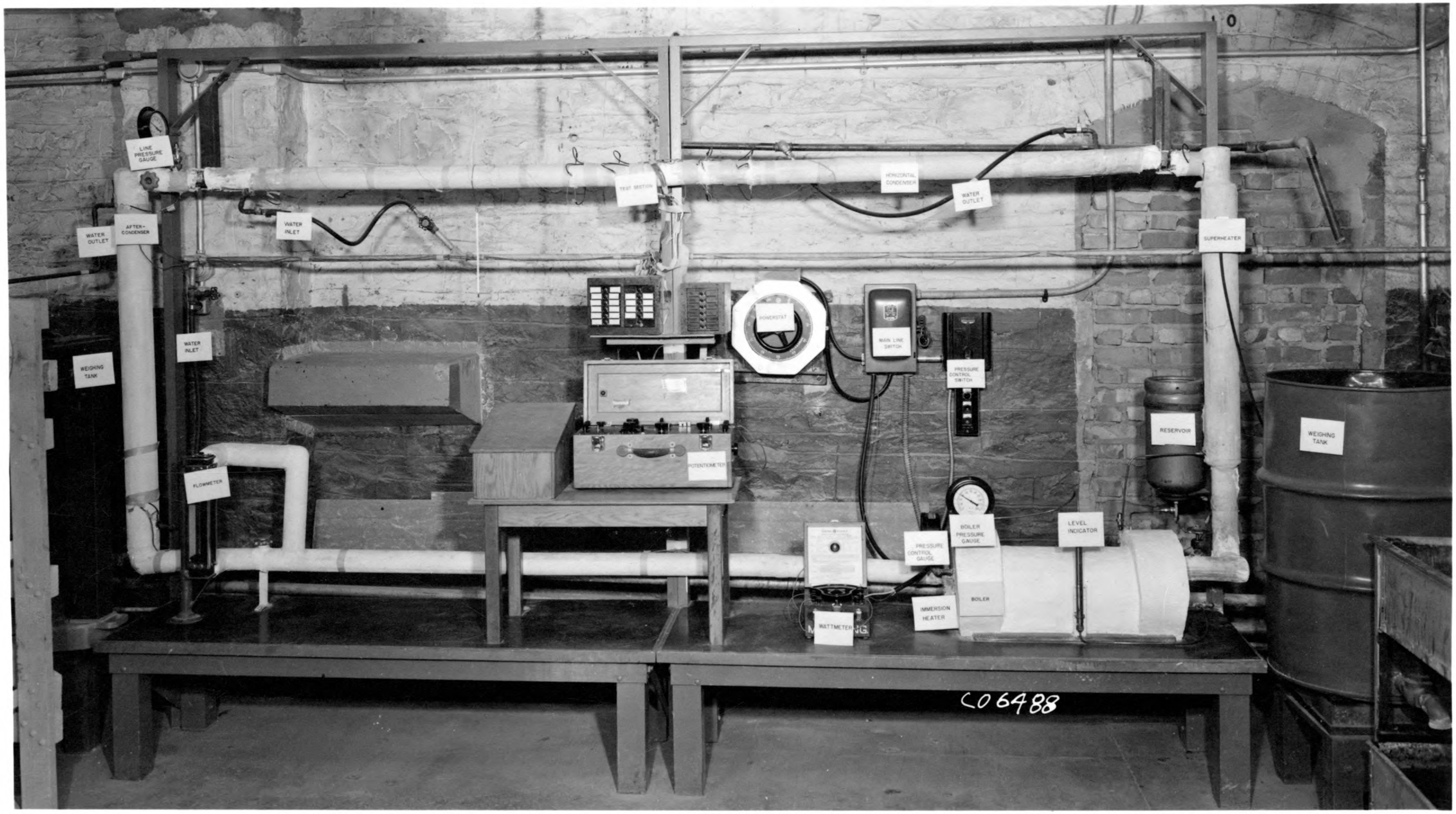

LINE PRESSURE GAUGE
WATER OUTLET
AFTER-CONDENSER
WATER INLET
TEST SECTION
HORIZONTAL CONDENSER
WATER OUTLET
SUPERHEATER
WEIGHING TANK
WATER INLET
FLOWMETER
POWERSTAT
MAIN LINE SWITCH
PRESSURE CONTROL SWITCH
POTENTIOMETER
RESERVOIR
WEIGHING TANK
BOILER PRESSURE GAUGE
LEVEL INDICATOR
PRESSURE CONTROL GAUGE
BOILER
IMMERSION HEATER
WATTMETER
C06488

PLATE III

Schematic diagram of the test apparatus for studying the condensation of Freon-12 inside a single horizontal tube.

PLATE III

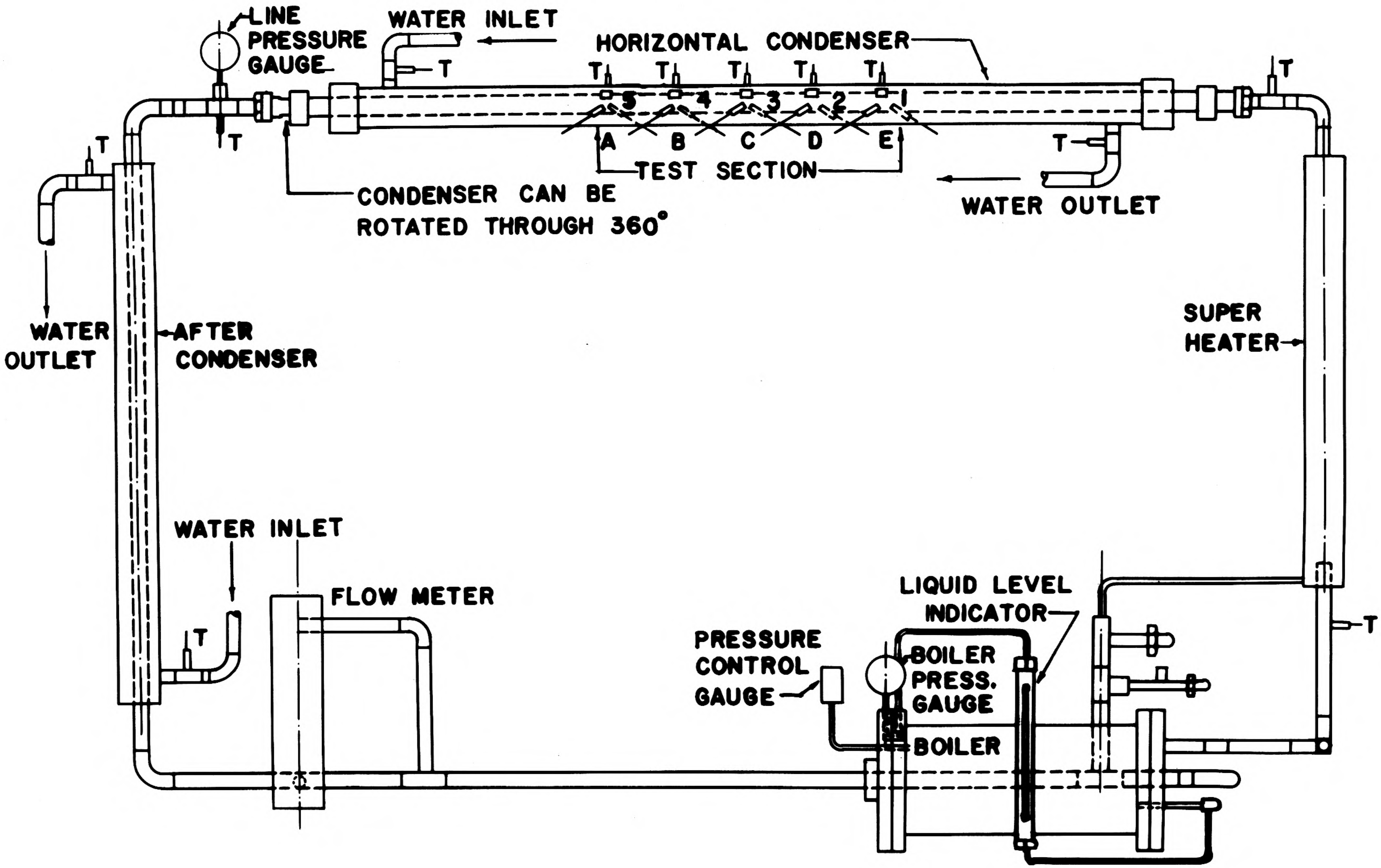

LINE
PRESSURE
GAUGE
WATER INLET
T
HORIZONTAL CONDENSER
T
T
T
T
T
5
4
3
2
1
A
B
C
D
E
TEST SECTION
T
T
T
CONDENSER CAN BE
ROTATED THROUGH 360°
WATER OUTLET
WATER
OUTLET
AFTER
CONDENSER
SUPER
HEATER
WATER INLET
T
FLOW METER
LIQUID LEVEL
INDICATOR
PRESSURE
CONTROL
GAUGE
BOILER
PRESS.
GAUGE
BOILER
T

PLATE IV

Photograph of the principal components of the test apparatus for studying the condensation of Freon-12 inside a single horizontal tube.

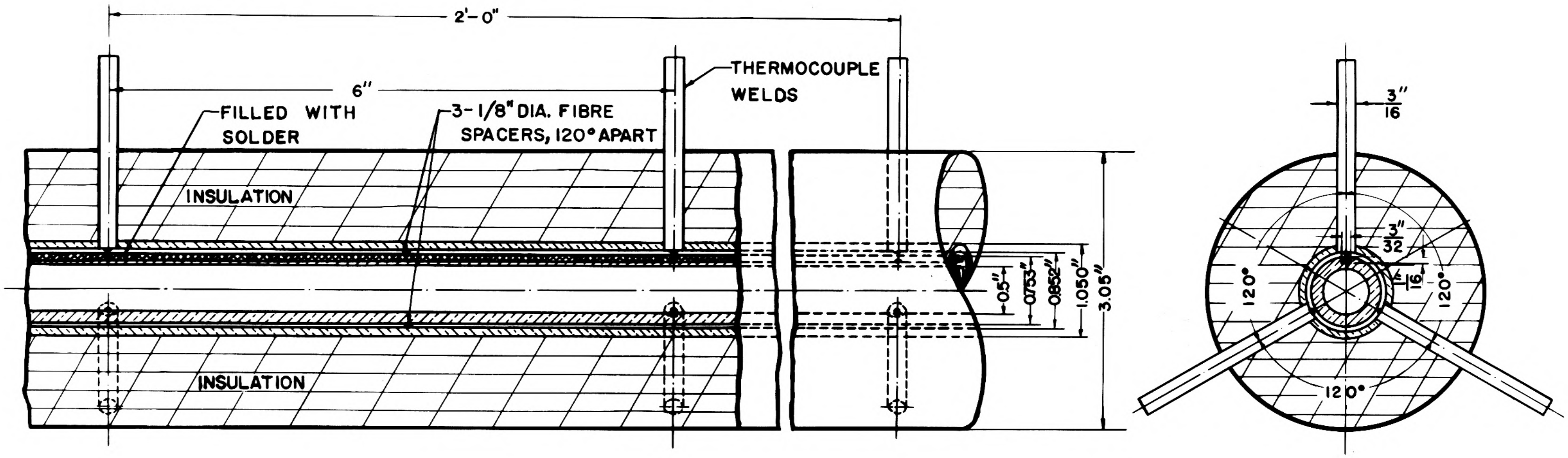
PLATE IV


AFTER-
CONDENSER
TEST SECTION
FLOWMETER
SUPERHEATER
CONDENSER
JACKET
BOILER

PLATE V

Sectional view of the test section for studying the condensation of Freon-12 inside a single horizontal tube.

PLATE V


2'- 0"
6"
THERMOCOUPLE WELDS
FILLED WITH SOLDER
3- 1/8" DIA. FIBRE SPACERS, 120° APART
INSULATION
INSULATION
0.5"
0.753"
0.852"
1.050"
3.05"
3"/16
3"/32
1/16
120°
120°
120°

would be a function of size other than diameter. A compromise value of 0.5 inch was selected. The outer pipe of this double pipe condenser was selected to insure turbulent flow of the cooling water at the anticipated flow rates. The length of the condenser was established at 10 feet to insure that the end effects would be minimized, to approximate practical designs, and to permit flexibility in the experimental program. The inner pipe was sealed and centered by three 1/8-inch diameter fiber spacers, 120 degrees apart at both ends, and at the center of the condenser. Arrangement for rotating the condenser through 360 degrees was made. The center two-foot section was established as the test section. Temperatures of cooling water and the inner pipe wall were measured at five points six inches apart. A sectional view of the test section is shown in Plate V. The entire apparatus was designed to accommodate the test condenser in a closed thermal circulation fluid system, heat being supplied by the boiler which generated the Freon-12 vapor. The test condenser was connected with the main line pipe by means of a threaded pipe union with a neoprene gasket.

In the determination of the film coefficient, accurate measurement of the pipe wall temperature presented the greatest difficulty, yet this measurement was the most important part of the experimental work. The final degree of accuracy obtained in such work is usually controlled by the accuracy of this measurement. Thermocouples were chosen for this work because of their economy and flexibility of installation.

The following requirements should be met in any installation involving thermocouples, Hebbard and Badger (4), P. 359:

1. The temperature recorded by any given junction must be that of the corresponding wall temperature.
2. The effect of heat conduction to the junction by the leads should be minimized or eliminated.
3. The characteristic of the normal film on the wall must not be disturbed by the installation of thermocouples.
4. Any installation should be in mutual agreement between different couples and should be capable of accurate reproduction.
5. The assembly should be sufficiently strong to withstand all conditions encountered during installation of the tube.
6. A minimum of time should be required for installation and calibration.
7. Frequent recalibration and attention to the couples should not be necessary.

Pipe-wall temperatures were measured by five No. 30 B. & S. gauge, copper-constantan thermocouples which were installed at six-inch intervals over a two-foot length along the pipe in the test section. A longitudinal groove 1/16 inch deep and 3/32 inch wide was milled in the pipe wall along the entire length of the condenser. The thermocouple junctions were made by spot welding. This method preserved the original insulation. The thermocouples were installed in the milled groove and covered with solder of approximately the same conductivity as the brass pipe. The leads were brought to plastic terminals at both ends of the condenser. The thermocouple wires were electrically insulated from the pipe except at the junction by applying insulating varnish over their original enamel and cotton coverings. Adverse thermal effects, such as the error caused by conduction along the leads, were minimized by this method of installation.

The temperature of the cooling water, which flowed through the annular space, was measured by thermocouples placed in the center of the inlet and outlet lines, approximately two inches from the jacket tees. The increase in cooling water temperature in the test section was measured with the thermocouples installed in wells which projected into the annulus between the inner and the outer pipes of the test condenser. Three thermocouple wells were installed 120 degrees apart, as shown in Plate V. The three thermocouples were joined together to form a thermopile. Freon-12 vapor temperatures were measured at three different places, namely, at the outlet of the boiler, at the inlet, and the outlet of the test condenser. They were measured by thermocouples placed in the center of the vapor line. The average vapor temperature in the test section of the condenser was taken as the arithmetic mean of the inlet and outlet temperature to the test condenser. The thermocouple wires were connected to a selector switch in an insulated box. The reference junction temperature was maintained at 32 degrees F. The room temperature was measured by a calibrated thermometer. A Leeds and Northrup portable potentiometer was used for measuring the thermocouple potentials. The thermocouples were calibrated before installation in a Leeds and Northrup thermocouple checking furnace by comparing them with a standard platinum-platinum-rhodium thermocouple. Calibration charts for the thermocouples were made from these data.

A sectional view of the superheater is shown in Plate VI. The superheater was designed to serve dual purposes: (1) to make sure that the vapor entering the test condenser was saturated or superheated; (2) to act as a liquid separator. The entrained liquid as well as any vapor condensed due to heat loss from the insulated pipe leading from the boiler was collected in the superheater and was returned to the main line at the inlet to the boiler.

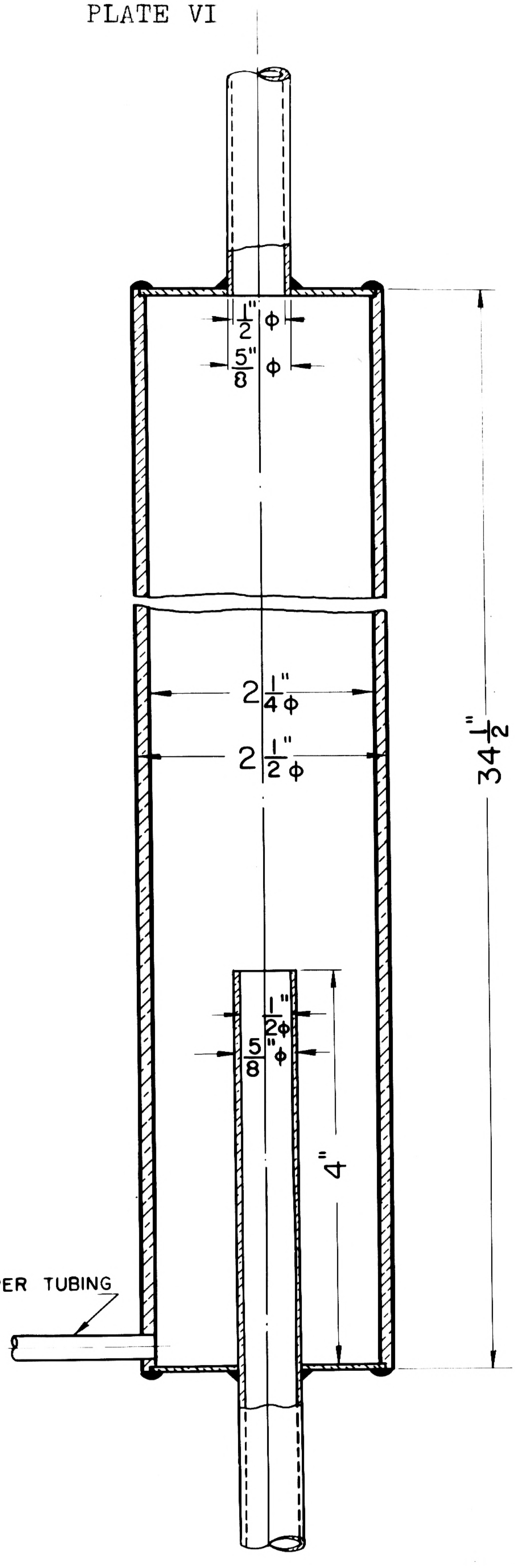
The after condenser was designed to insure that all the vapor was condensed before it entered the boiler. The flow rate of Freon-12 condensate was measured by means of a full-view safety shield type Brooks Rotameter in gallons per minute, with a minimum and maximum flow capacity of 0.05 and 0.55 gallon per minute, respectively.

The boiler was a 6-1/32-inch inside diameter, 20-inch long steel cylinder, with 1-1/4-inch thick steel flanges welded to it on both ends. The material of the boiler was selected to withstand corrosion by Freon-12. A 20-1/4-inch long vapor tube (dry pipe) located near the top of the boiler was used to make sure that only vapor entered the main line. The heating element used in generating the vapor was sized so that a sufficient quantity of water, to allow accurate measurements over a 10- or

PLATE VI

Sectional view of the superheater.

PLATE VI



15-minute period, would flow through the condenser. A 5-kw "screw-in" immersion heater, 220-volt, a-c, located in the lower half of the boiler, was used as the heating element. A sectional view of the boiler assembly is shown in Plate VII. The 5-kw heater was determined to be largest which could be used without extensive modification of the electrical supply system in the laboratory. A heater to supply energy was selected for ease of control and economy as compared to a mechanical compressor of the same power. Pyrex glass liquid level indicator was used to check the level of the Freon-12 liquid in the boiler.

Two bourden-tube pressure gages with 0/300-psi range, were used to measure the boiler pressure and the main-line pressure at the outlet of the test condenser.

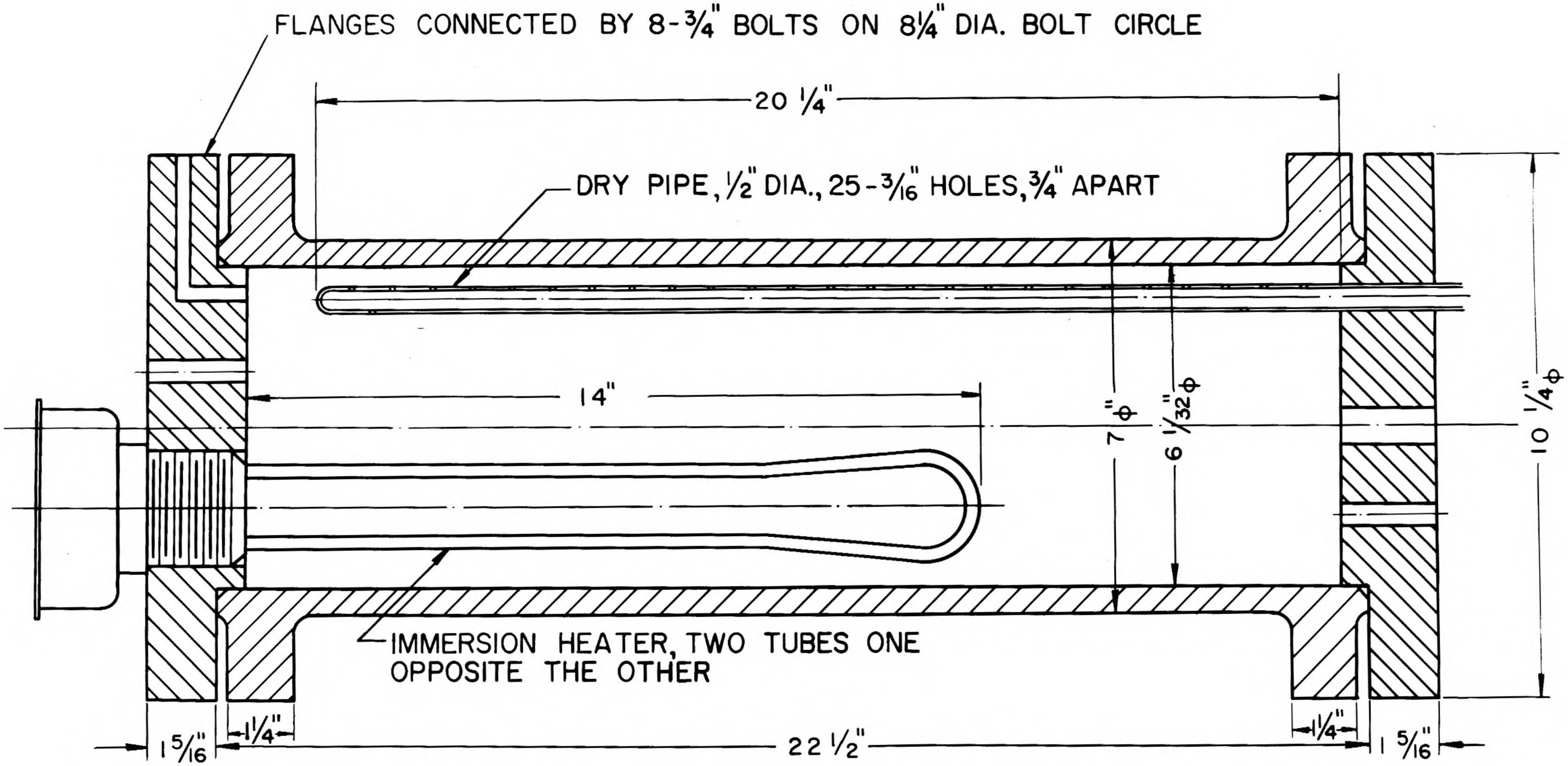
The power input could be controlled over a wide range which permitted operation over a corresponding wide range of film-temperature drops. A powerstat, variable transformer, input 230 volts, 50/60 cycles, output 0/270 volts, 28 amperes, 7.5 kva, was used to adjust the power input to the heater. To limit the pressure rise in the boiler, a bourden-tube pressure control gage with maximum setting of 200 psi was used.

The design of the apparatus was also based on the cooling medium available and methods available for its measurement of flow. Water at line pressure and temperature was used as the cooling medium. The most accurate means of measuring its rate of flow was by weighing the amount flowing into a tank over a specified period of time.

PLATE VII

Sectional view of the boiler assembly.

PLATE VII



FLANGES CONNECTED BY 8-3/4" BOLTS ON 8 1/4" DIA. BOLT CIRCLE
20 1/4"
DRY PIPE, 1/2" DIA., 25-3/16" HOLES, 3/4" APART
14"
7"φ
6 1/32"φ
10 1/4"φ
IMMERSION HEATER, TWO TUBES ONE OPPOSITE THE OTHER
1 5/16"
1 1/4"
22 1/2"
1/4"
1 5/16"

The whole system was designed in such a way that it was possible to isolate any part of the system by closing valves at different places. All piping was insulated by one-inch thick standard pipe insulation, and the boiler was insulated by approximately one-inch thick coating of asbestos cement to minimize the heat loss.

OPERATION OF EQUIPMENT

Before assembling the apparatus, all parts were carefully cleaned to prevent corrosion and to insure film-type condensation in the test condenser. Care was taken against the introduction of dirt particles when the apparatus was assembled.

Operation of the apparatus was begun by evacuating the entire system with a vacuum pump. The entire system was kept under a vacuum for about 24 hours to check for leaks. The valve to the Freon-12 reservoir was opened and boiler and pipings were filled with liquid Freon-12 until the heating element was immersed in the liquid. The entire system was again tested for leaks by means of a Freon leak detector. When it was certain that there were no leaks in the entire system, the apparatus was ready for the run. The heater load was set at a predetermined value by means of the powerstat. The cooling water valve was opened until the flow rate was sufficient to produce turbulent flow through the annular space. The flow rate was held constant during the entire series of runs. The system was allowed to run for about a three-hour period, to insure equilibrium conditions. Equilibrium was determined by periodic temperature measurements. Measurements of temperatures, pressures, Freon-12 flow rate, cooling water flow rate, and power input to the heater were taken.

The Freon-12 flow rate was measured with a Rotameter in gallons per minute, pressures with Bourden-tube gages in pounds per square inch, temperatures with calibrated copper-constanton thermocouples and portable potentiometer in millivolts, power input with a wattmeter in kilo-watts, atmospheric pressure with mercury barometer in inches of mercury, room and reference junction temperatures with calibrated thermometers in degrees F, and cooling water flow with a tank on a platform scale in pounds per hour. Temperatures were converted from millivolts to degrees F by using thermocouple calibration charts.

Experimental data were taken over a wide range of power inputs to the boiler, to get wide range of vapor velocities and the film coefficients of heat transfer. The top position of the pipe-wall thermocouples was considered to be the 0-degree position. After the first series of runs in this position, the test condenser was rotated through 45 degrees, 90 degrees, 135 degrees, and 180 degrees. Data in these positions were taken by repeating the same procedure as used in the 0-degree position.

Since the maximum capacity of the pressure control gage was 200 psi, the upper limit of the power input was limited to about 4.2 kw. Superheater and after condenser were not used during these runs. During the operation of the apparatus, the liquid level in the boiler was maintained so that it covered the immersion heater. The entire system was tested for leaks several times during operation.

EXPERIMENTAL DATA AND CALCULATIONS

Data

A total of 142 runs were made. The observed data are recorded in Table 1 in Appendix C. These runs were made for five pipe-wall thermocouple positions of 0 degree, 45 degrees, 90 degrees, 135 degrees, and 180 degrees, as shown in Plate VIII.

Attempts were made to take the readings over a wide range of heat inputs to get a wide range of mass velocity and film coefficient of heat transfer. The heat input was limited by the setting of the pressure control.

The thermocouple readings were converted to temperatures using the individual calibration for each couple.

Calculations

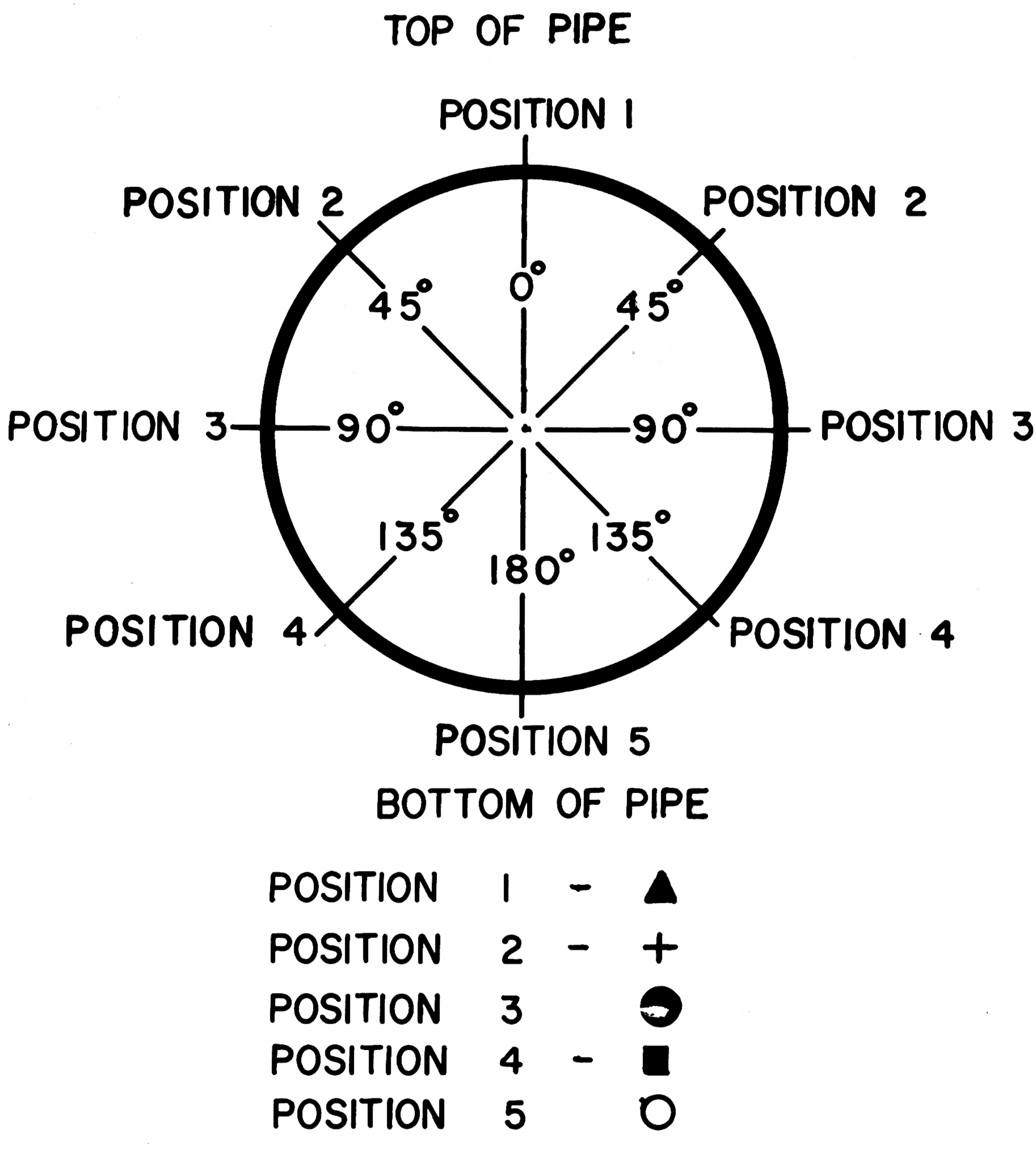
Physical properties of the Freon-12 vapor were evaluated at the bulk temperature. The bulk temperature of Freon-12 vapor was taken as the arithmetic mean of the inlet and the outlet temperatures to the test condenser. These properties are given in Table 2, in Appendix D.

The calculated data are given in Table 3 in Appendix E.

PLATE VIII

Diagram showing the condenser tube position, as indicated by the location of the thermocouple.

PLATE VIII


TOP OF PIPE
POSITION 1
POSITION 2
POSITION 2
0°
45°
45°
POSITION 3
90°
90°
POSITION 3
135°
135°
180°
POSITION 4
POSITION 4
POSITION 5
BOTTOM OF PIPE
POSITION 1 - ▲
POSITION 2 - +
POSITION 3
POSITION 4 - ■
POSITION 5 ○

A sample calculation is given in Appendix F. The Freon-12 vapor velocity, V, feet per second, the flow rate of condensate, W, pounds per hour, and the mass velocity, G, pounds per hour per square foot, were calculated from the measured rate of flow of Freon-12 in gallons per minute.

The heat transfer rate in Btu per hour in the test section could be evaluated (1) from the quantity of condensate formed in the test section, or (2) from the cooling water rate and its corresponding temperature rise. The value used in the following calculations was that obtained from the measurement of the amount of cooling water and its rise in temperature for the following reasons:

1. The rise in temperature of cooling water in the test section was measured very accurately.
2. The amount of Freon-12 vapor condensed in the test section was not measured.

The temperature drop across the Freon film was calculated as follows. The temperature of the outside surface of the test condenser was measured at five places--1, 2, 3, 4, and 5--along the test section, as shown in Plate III. The temperature of the outside surface was taken as the arithmetic average of these measurements. The temperature drop across the pipe wall was calculated, using the logarithmic mean area. The temperature of the inside condensing surface was found by adding this temperature drop to the outside surface temperature. The temperature drop across the film is the difference, ΔT_c, in bulk temperature of Freon-12 vapor and the calculated condensing surface temperature. An additional resistance, or "fouling factor", which might be present due to foreign material in the Freon-12 vapor stream, was negligible because of:

1. High purity liquid was used to produce the vapor.
2. The condenser tube was thoroughly cleaned.
3. Care was taken during assembly to prevent the introduction of foreign material into the apparatus.

The heat flux, Q/A_1, in Btu per hour per square foot was calculated by dividing the rate of heat transfer in test section by the condensing surface area. The heat flux, Q/A_1, divided by the corresponding temperature drop, ΔT_c, across the film gave the film coefficient of heat transfer. The following relations were used in the above calculations:

$$Q = M\ Cpw\ \Delta tw = k_m A_m \frac{\Delta t_b}{\Delta x} = h_f \cdot A_1 \cdot \Delta T_c \qquad (10)$$

DISCUSSION

Graphical interpretation of the test results is shown in Figs. 1 to 6 for all five positions of the tube. Figure 1 shows the wall temperatures along the test section. The deviation of the pipe-wall temperature from a uniform temperature drop was considered to be due to an error in the thermocouple measurements at positions 2 and 3. The temperature difference, ΔT_c, could be calculated from this figure. The area between the Freon-12 vapor bulk temperature and pipe-wall temperature curves

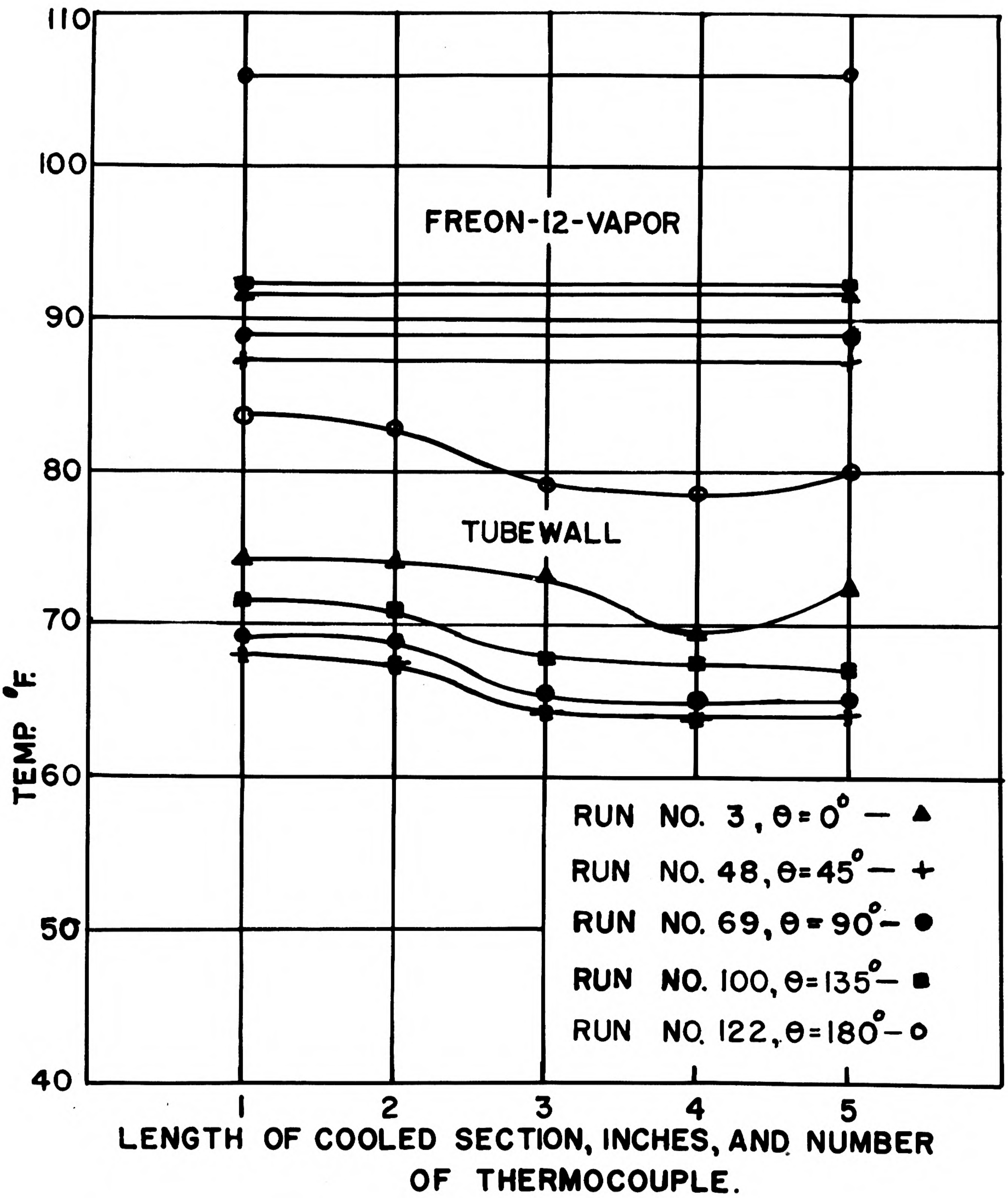


Fig. 1. Average Freon-12 vapor temperatures and tube-wall temperatures along the test section.

divided by the length of the pipe will give the temperature difference, ΔT_c. The temperature differences, ΔT_c, at the pipe-wall thermocouple positions are given by Fig. 2. These values of temperature difference, ΔT_c, for different positions of the pipe were taken from Fig. 6 at nearly equal values of heat flux, Q/A_1. The temperature difference, ΔT_c, is a maximum in position 1 and a minimum in position 5. This was due to the increase of film thickness from top to bottom of the pipe, as shown in Plate I. It was very difficult to hold all conditions identical for all positions of the pipe for comparison of the data.

The variation of film coefficient with mass velocity over a limited range is shown in Fig. 3. The film coefficient, h_f, increased with the increase in mass velocity, G. This could be due to the increase of turbulence in the Freon film. The results of this experiment showed that the heat transfer coefficients in the range of heat flux and temperature differences investigated, range from a value of about 295 to 950 B/hr-ft^2 °F. Figure 4 shows the increase in heat flux with increase in mass velocity. The decrease in film coefficient, h_f, with increase in temperature drop, ΔT_c, across the film is shown in Fig. 5, which confirmed the theoretical prediction that the heat transfer coefficient decreases with an increase in film temperature drop. This is attributed to the fact that an increase in film temperature difference results in an increased flow of heat and a corresponding increased film thickness which decreases film coefficient, h_f. Figure 6 shows the relation between the heat flux and the film temperature difference.

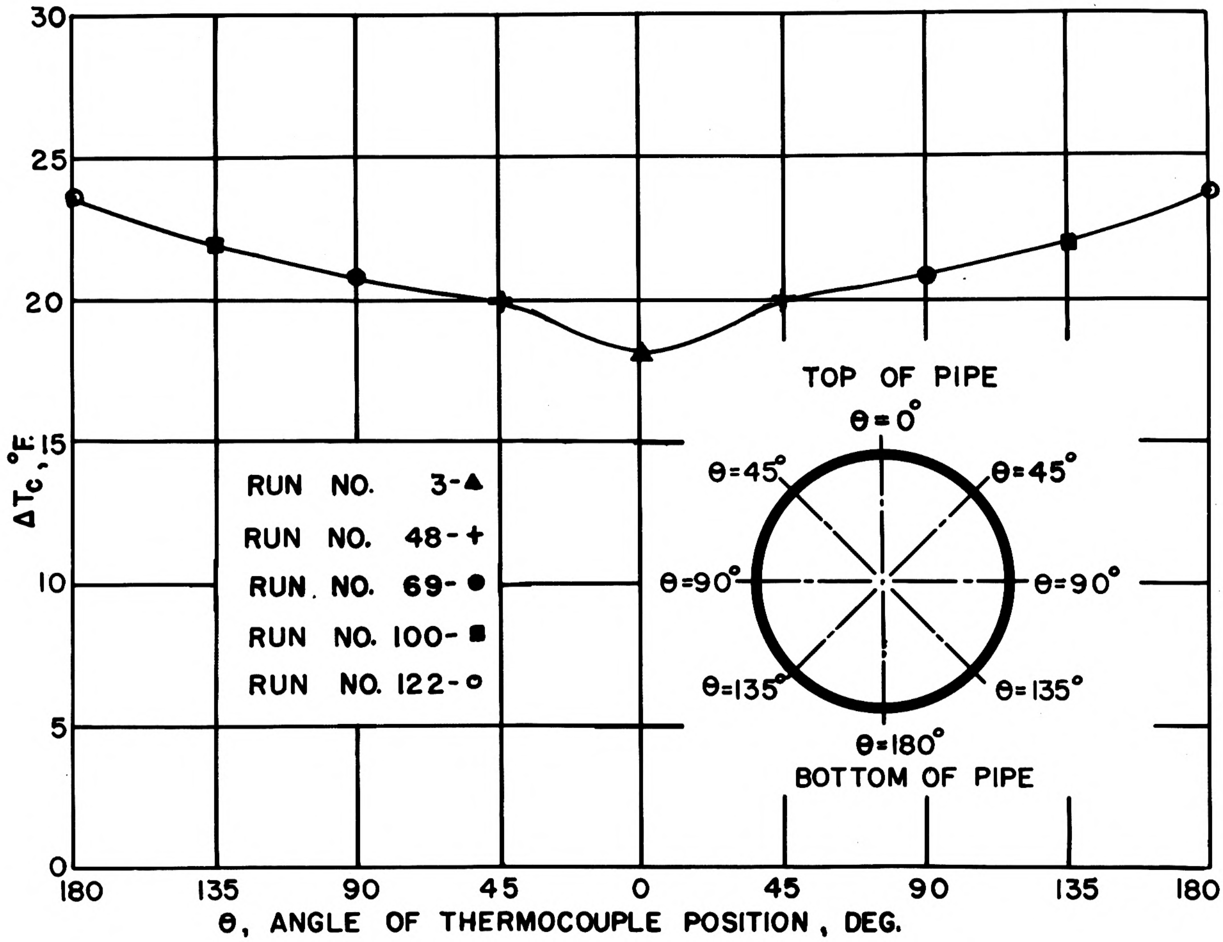


Fig. 2. Relation of temperature difference between the condensing surface and Freon-12 vapor, ΔT_c, °F, to the angle indicated by the thermocouple positions, θ, degree, for nearly equal heat flux, Q/A_1.

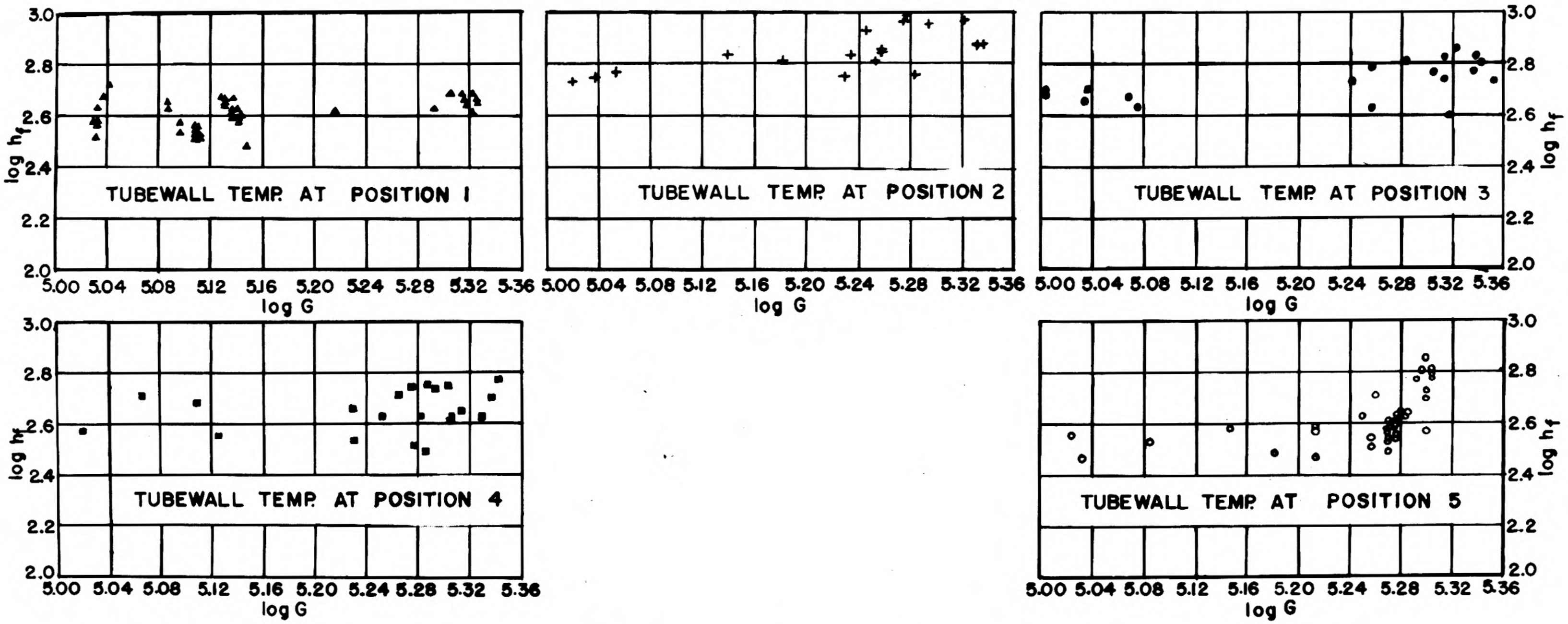


Fig. 3. Relation of film coefficient of heat transfer, h_f, B/hr-ft^2 °F, to the mass velocity, G, lb/hr-ft^2, during the condensation of Freon-12 inside a single horizontal tube.

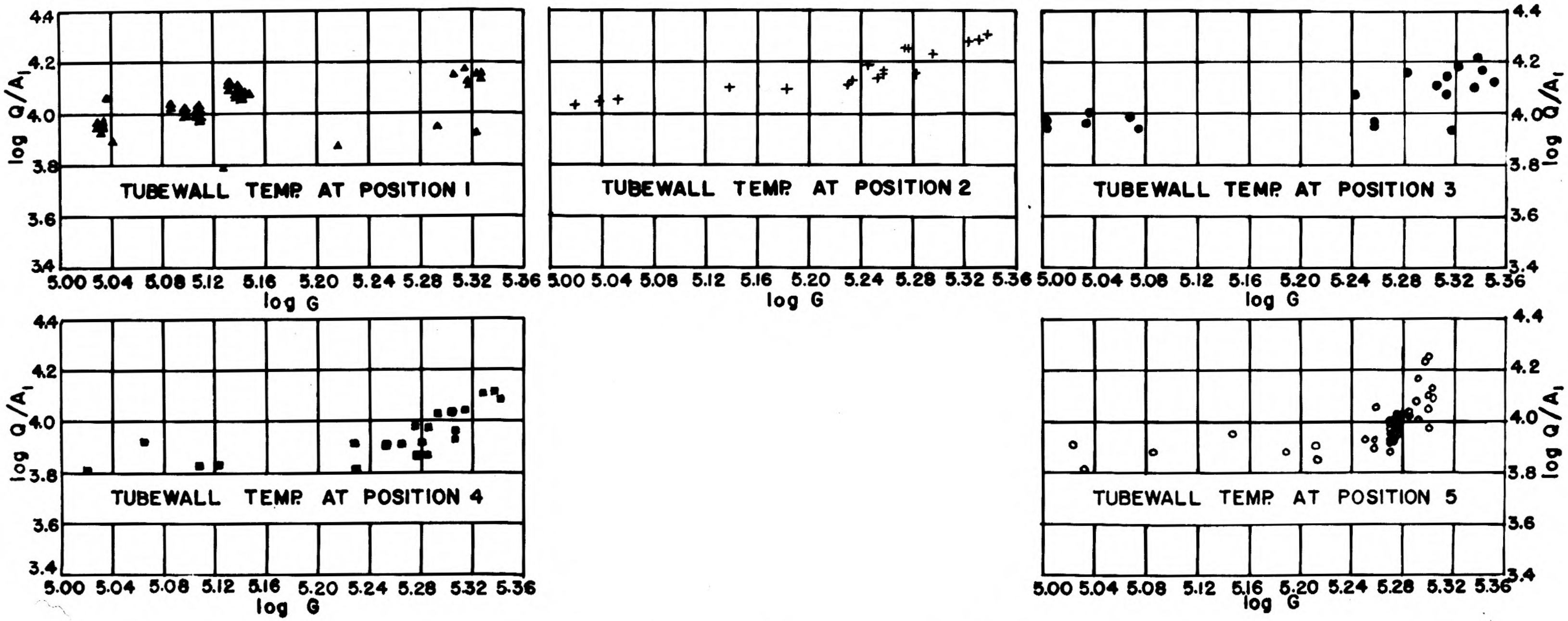


Fig. 4. Relation of heat flux, Q/A_1, $B/hr\text{-}ft^2$, to the mass velocity, G, $lb/hr\text{-}ft^2$, during the condensation of Freon-12 inside a single horizontal tube.

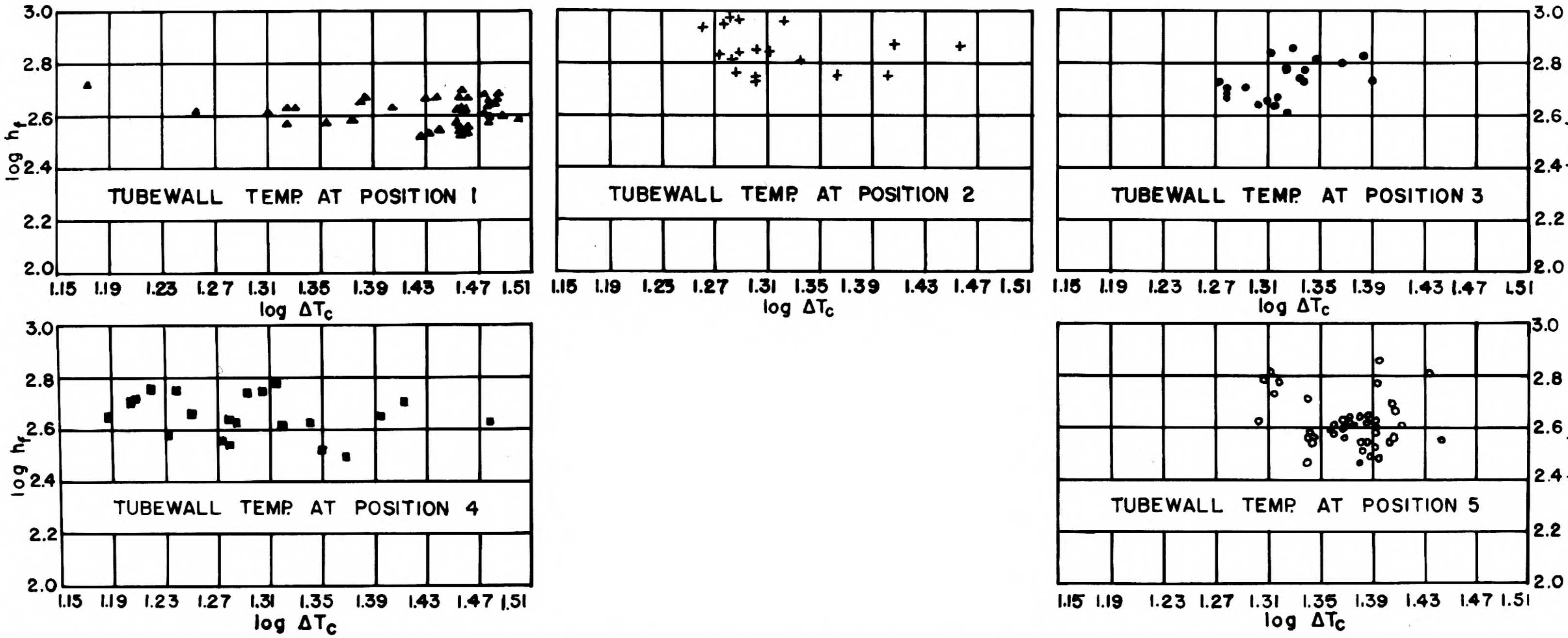


Fig. 5. Relation of film coefficient of heat transfer, h_f, B/hr-ft^2 °F, to the temperature difference between the condensing surface and Freon-12 vapor, ΔT_c, °F, during the condensation of Freon-12 inside a single horizontal tube.

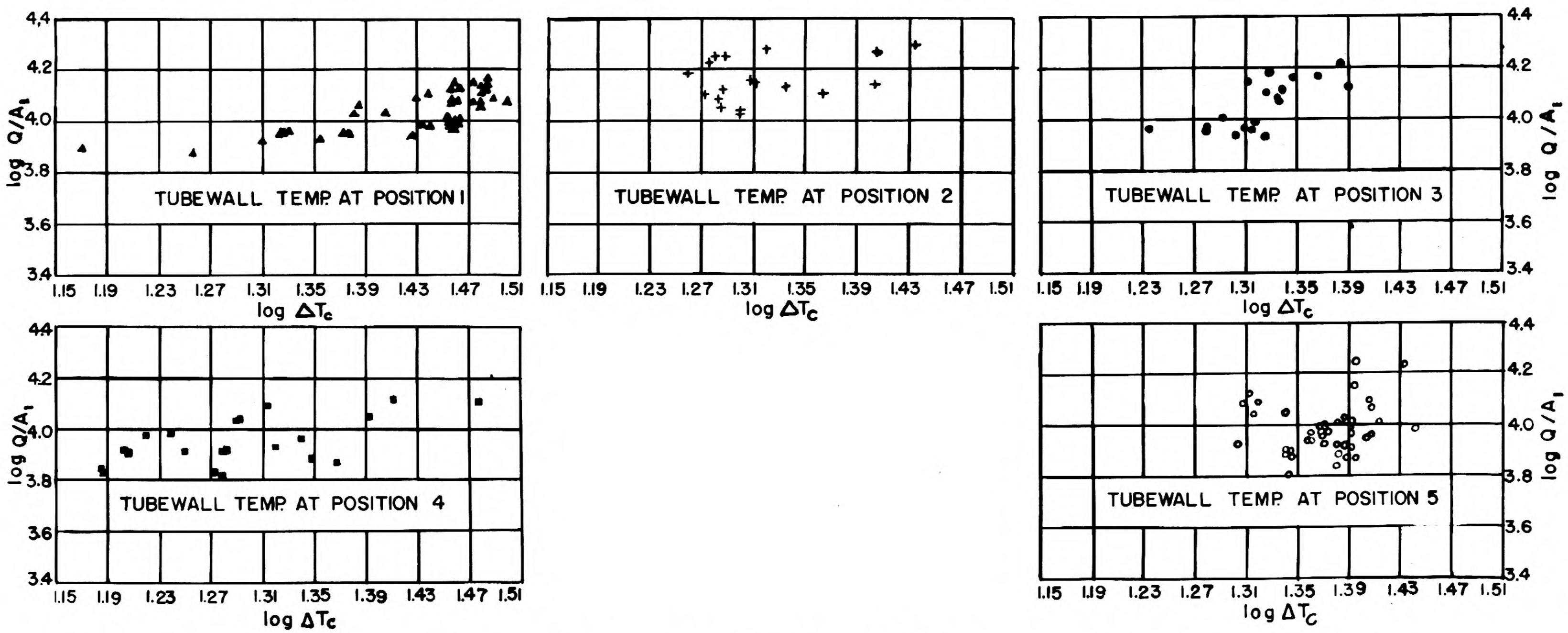


Fig. 6. Relation of heat flux, Q/A_1, B/hr-ft^2, to the temperature difference between the condensing surface and Freon-12 vapor, ΔT_c, °F, during the condensation of Freon-12 inside a single horizontal tube.

The experimental data were correlated using equation 9:

$$\frac{h_f D}{k_b} = C \left(\frac{DG}{\mu_b}\right)^n$$

where n and C are constants to be determined. The calculations are presented in Table 3. The Nusselt number, Nu, was plotted against the Reynolds number, Re, on log-log graph paper for all five positions of the condenser pipe-wall thermocouples, as shown in Fig. 7. The equation of the best fitting straight line was found by the method of least squares (Appendix G). The following equations were obtained for the respective positions.

Position 1: $\hat{Y} = 0.2216\ X + 1.6593$ (11a)

Position 2: $\hat{Y} = 0.5633\ X + 0.4867$ (11b)

Position 3: $\hat{Y} = 0.3416\ X + 1.2730$ (11c)

Position 4: $\hat{Y} = 0.2462\ X + 1.5720$ (11d)

Position 5: $\hat{Y} = 0.6866\ X - 0.2657$ (11e)

where $\hat{Y} = \log Nu$ and $X = \log Re$

n = coefficient of X

$\log_C$ = constant

The average value n and C were calculated by taking a weighted average of the values found for individual positions, to represent all positions of the pipe. The values of n and C were found to be 0.4013 and 1.017 respectively. The equation which represents all of the experimental data was found to be:

$$\hat{Y} = 0.4013\ X + 1.0071 \qquad (12)$$

The equation 9 becomes:

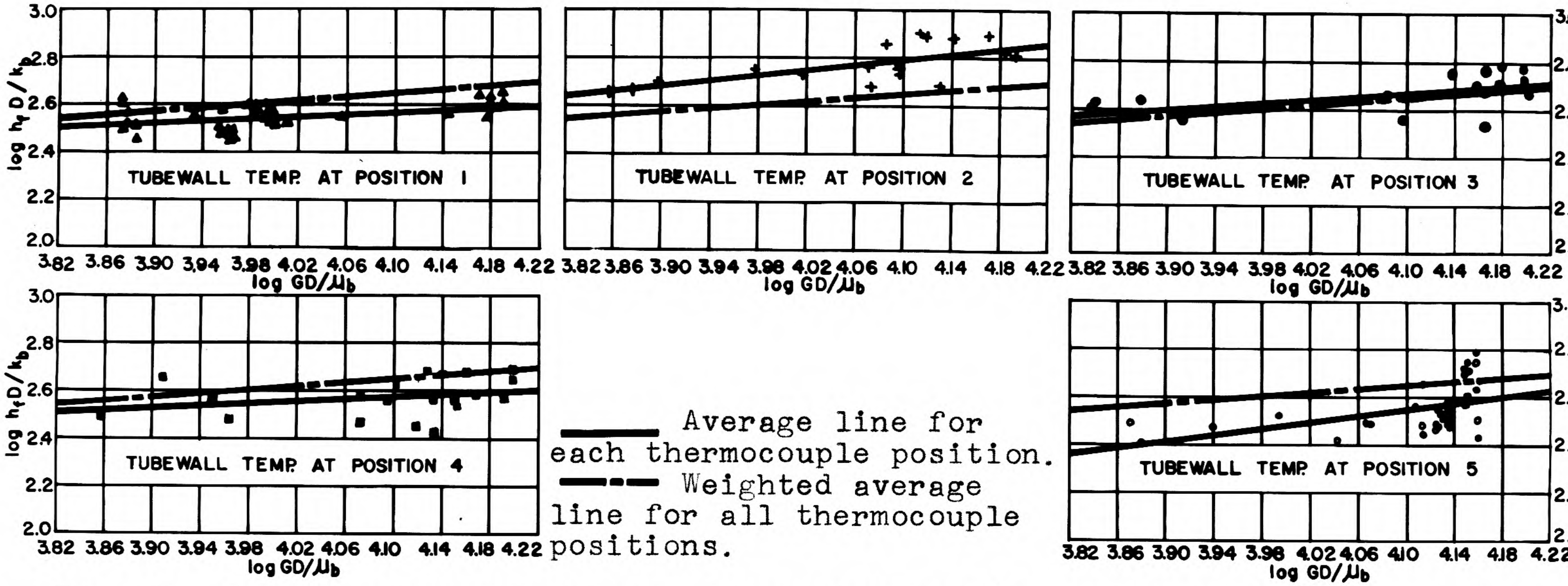


Fig. 7. Relation between the Nusselt number, $h_f D/k_b$, and the Reynolds number, GD/μ_b, for different tube-wall thermocouple positions during the condensation of Freon-12 inside a single horizontal tube.

$$\frac{h_f D}{k_b} = 10.17 \left(\frac{DG}{\mu_b}\right)^{0.4013} \qquad (13)$$

Equation 13 is plotted in Fig. 7 with equations 11a to 11e.

The correlation equation resulting from this investigation holds for 1/2-inch, two-foot long pipe, and for Reynolds numbers in the range from 6800 to 16100. Inspection of Fig. 7 shows that for a given vapor-in-tube condenser the film coefficient increases with the increase in Reynolds number, i.e., mass velocity. This was shown in Fig. 3.

The vertical distance of any point from this line shows the deviation of the experimental data from the developed correlating equation. The standard deviation of Y_1 and that of the slope were calculated for all five positions of the pipe-wall thermocouples. Equations for the standard deviation of Y were also obtained for all these positions. These calculations are given in Appendix H, with the detailed discussion on the method of least squares. The standard deviation has been found to be a good measure of the variability of a set of numerical measurements about their mean regression line, chosen by the method of least squares. The more dispersed they are about the mean, the larger the standard deviation tends to be. The slope of the individual position line estimates the average change in the Y-measurements for each unit increase in the X-measurements. Its accuracy is measured by its standard deviation, S_b. The equations found for the standard deviation of Y give a more specific measure of the accuracy of the value calculated from the individual equations of the positions.

It is interesting to note that the Nusselt number is a function of the 0.4013 power of the Reynolds number. This is approximately one-half of the 0.8 power in the equation for the film coefficient of liquids and gases in turbulent flow being heated or cooled inside tubes with no phase change, McAdams (8), P. 219.

Equation 13 has not been proved valid outside the ranges of experimental data. This equation should be used for only horizontal, vapor-in-tube cases. Jacob (6), P. 682-684, investigated condensation of saturated and superheated steam inside a horizontal tube. He obtained much higher rates of heat transfer in this position than that obtained in any other position. Unfortunately, his original data were not available for a quantitative comparison.

Nusselt obtained the following dimensionless equation for film-type condensation on the outside surface of a single horizontal tube:

$$h_f = 0.725 \sqrt[4]{\frac{k^3 \rho^2 g \lambda}{D \mu \Delta t}} \qquad (14)$$

For the same case, White (7), P. 689-693, in his investigation on Freon-12, obtained the following equation:

$$h_f = 0.63 \sqrt[4]{\frac{k^3 \rho^2 g \lambda}{D \mu \Delta t}} \qquad (15)$$

The experimental data obtained by White under conditions as nearly ideal as possible are 13 per cent below the low values predicted by Nusselt's equation for condensation of Freon-12 at elevated pressure.

It is interesting to note that Young and Wohlenberg (12), P. 787, in their investigation of condensation of Freon-12 on the outside surface of a bank of horizontal tubes, obtained an average constant in Nusselt's equation of 0.655 for the top tube. Observation of the tube through the sight glass in their experiment showed that under all conditions and rates of condensation, a very quiet, streamline film formed on the top tube in the bank. At the bottom of the tube, the liquid formed drops which fell to the second tube.

In this investigation of the condensation of Freon-12 inside a horizontal tube, many difficulties were experienced. The fraction of the Freon-12 vapor condensed in the test section should be introduced in equation 13. In using this equation, the total flow of Freon-12 was considered. To make sure that only saturated vapor enters the test section, it should be superheated. Also, arrangements to find the quality of the vapor at the inlet and at the outlet of the test section should be made. It is also advisable to have a sight glass at the inlet and at the outlet of the test section to observe the type of the condensation taking place inside the horizontal tube. More instrumentation should be provided to get more information about the condensation of Freon-12 inside a horizontal tube.

SUMMARY

Film coefficients of heat transfer for Freon-12 vapor condensing inside a single horizontal tube were investigated. Over a range of Reynolds numbers, DG/μ_b, of 6800 to 16100, the film coefficients of heat transfer, h_f, ranged from 295 to 950 B/hr-ft^2 °F, for a range of heat fluxes Q/A_1, of 6000 to 20200 B/hr-ft^2. The following dimensionless equation was developed to fit the experimental data:

$$\frac{h_f D}{k_b} = 10.17 \left(\frac{DG}{\mu_b}\right)^{0.4013} \qquad (13)$$

The following conclusions may be drawn for the range of variables investigated:

1. The film coefficient of heat transfer decreases with the increase in temperature drop across the line.
2. An increase in the mass velocity will increase the film coefficient of heat transfer, apparently through an increase in the turbulence of the film.
3. Heat transfer rate increases with increasing mass velocity.
4. The correlation obtained can be used to predict the film coefficient of heat transfer for Freon-12 inside a horizontal tube.

ACKNOWLEDGMENTS

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APPENDICES

APPENDIX A

NOMENCLATURE

A Cross-sectional area of the inner tube of the horizontal condenser, ft^2.

A_1 Area of inside surface of the inner tube, ft^2.

A_2 Area of outside surface of the inner tube, ft^2.

A_m Logarithmic mean area, ft^2. $A_m = \dfrac{A_2 - A_1}{\ln \dfrac{A_2}{A_1}}$

C_{p_f} Specific heat of Freon-12 condensate at constant pressure, B/lb °F.

C_{p_w} Specific heat of cooling water at constant pressure, B/lb °F.

D_1 Inside diameter of the inner tube, ft.

D_2 Outside diameter of the inner tube, ft.

D_e Equivalent diameter, ft. $D_e = D_2 - D_1$.

G Mass velocity of Freon-12 condensate, lb/hr-ft^2.

h_a Film coefficient of heat transfer between outside surface and cooling water, B/hr-ft^2 °F.

h_f Film coefficient of heat transfer between inside surface and condensing Freon-12 vapor, B/hr-ft^2 °F.

k Thermal conductivity of the Freon-12 condensate, B/hr-ft °F.

k_m Thermal conductivity of the material of the inner tube, mean value, B/hr-ft °F.

M Weight rate of cooling water, lb/hr.

Q Rate of heat transfer to cooling water in test section, B/hr.

$\frac{Q}{A}$ Heat flux, B/hr-ft^2.

Δt Temperature difference between inlet and outlet cooling water to the test section, °F.

Δt_b Temperature difference between inside and outside surface of the inner tube, °F.

ΔT_c Temperature difference between the Freon-12 condensing vapor and the inside surface of the inner condenser tube, °F.

V Freon-12 vapor velocity, ft/sec.

W Flow rate of Freon-12 condensate, lb/hr.

Δx Thickness of the inner condenser tube, ft.

ρ Density of Freon-12 condensate, lb/ft^3.

μ Absolute viscosity of Freon-12 condensate, lb/hr-ft.

θ Angle indicating thermocouple position, degree.

λ Heat of vaporization, B/lb.

Γ Mass rate of condensate per unit length of circumference, lb/hr-ft.

g Gravitational constant, ft/sec^2.

ϕ $\left[k^3 \rho_f^2 g/\mu_f^2\right]^{1/3}$

APPENDIX B

DESIGN DATA

1. To find the depth of the groove in the inner condenser pipe (Seely, Advance mechanics of material, P. 66, 1932).

Thin-wall formula: $S = \dfrac{P_r}{(r_2 - r_1)}$

Thick-wall formula: $S = \dfrac{(r_2^2 + r_1^2)}{(r_2^2 - r_1^2)}$

where S = stress in the pipe wall, psi

P = pressure on the pipe wall, psig

r_1 = inside radius of the inner pipe, inch

r_2 = outside radius of the inner pipe, inch

r = average radius of the inner pipe, inch. $r = \dfrac{r_1 + r_2}{2}$.

$r_1 = \dfrac{0.5}{2} = 0.25$ in $\qquad r_2 = \dfrac{0.753}{2} = 0.3765$ in

$$S = P\left[\frac{\overline{0.3765}^2 + \overline{0.25}^2}{\overline{0.3765}^2 - \overline{0.25}^2}\right] = P\left[\frac{0.1419 + 0.0625}{0.1419 - 0.0625}\right] = P\left[\frac{0.2044}{0.0794}\right]$$

$= 2.58\ P$

If P = 150 psig, $S = 2.58 \times 150 = 387$ psi

If P = 200 psig, $S = 2.58 \times 200 = 516$ psi

If P = 250 psig, $S = 2.58 \times 250 = 645$ psi

Maximum allowable working stress for brass up to 150°F

= 5000 psi (Mark's Handbook, p. 606)

Using thin-wall formula, $5000 = 250 \times 1/4 \times 1/t$, where $t = r_2 - r_1$

$$t = \frac{250}{5000 \times 4} = 0.0125 \text{ in}$$

Hence maximum allowable depth of the groove

$= 0.126 - 0.0125 = 0.1135$ inch.

It was decided to mill a 1/16-inch deep and 3/32-inch wide groove along the inner pipe.

2. Calculation of cooling water, assuming Freon-12 entering the test condenser as saturated vapor and complete condensation in the test condenser.

Cross-sectional area of the annular space

$$= A_a = \frac{\pi}{4 \times 144} (\overline{0.812}^2 - \overline{0.753}^2) = 0.000508 \text{ foot}^2$$

Assume total heat input in the boiler = 5 kw

= 17,065 B/hr

and temperature rise of water = $\Delta tw = 30°F$

Total heat transferred to cooling water in test condenser

$$Q = M \, C_{p_w} \Delta t_w$$

$C_{p_w} = 1.0$ B/lb °F (1), P. 462

$$\therefore M = \frac{Q}{C_{p_w} \Delta t_w} = \frac{17065}{1 \times 30} = 569 \text{ lb/hr}$$

$$\therefore \text{Mass velocity of water} = \frac{569}{0.000508} = 1,120,000 \text{ lb/hr-ft}^2$$

Velocity of water in annular space =

$$V_w = 1,120,000 \frac{\text{lb}}{\text{hr-ft}^2} \times \frac{1 \text{ hr}}{3600 \text{ sec}} \times \frac{\text{ft}^3}{62.4 \text{ lb}} = 4.99 \text{ ft/sec}$$

Equivalent diameter $= D_e = \dfrac{D_2 - D_1}{12} = \dfrac{0.812 - 0.753}{12}$

$= 0.00492$ foot

Assume average temperature of water = 70°F

$\mu_w = 0.978$ centipoise $= 2.37$ lb/hr-ft (1), P. 484

$$R_e = \frac{D_e G}{\mu_w} = \frac{0.00492 \times 1{,}120{,}000}{2.37} = 2325$$

Reynolds' number shows that the flow of cooling water is turbulent flow.

3. To calculate the film coefficient of heat transfer of condensing Freon-12.

Equation for horizontal annular flow of water in a turbulent motion:

$$\frac{h_a D_e}{k_w} = 0.023 \left(\frac{D_e G_w}{\mu_w}\right)^{0.8} \left(\frac{c_p \mu_w}{k_w}\right)^{0.4}$$

For water at 70°F

$\mu = 2.37$ lb/hr-ft (1), P. 484

$k = 0.356$ B/hr-ft °F (1), P. 484

$c_p = 1.0$ B/lb °F (1), P. 462

$$h_a = \frac{0.023 \times 0.356}{0.00492} (2325)^{0.8} \left(\frac{1 \times 2.37}{0.356}\right)^{0.4}$$

$$= 1.665 \times 490 \times 2.132 = 1738 \text{ B/hr-ft}^2 \text{ °F}$$

Area of the outside surface of the inner tube for 10-foot length $= 10 \times \pi \times \dfrac{0.753}{12} = 1.968 \text{ ft}^2$

Assume $\Delta t_m = 35°$

$$Q = uA \Delta t_m$$

$$\therefore u = \frac{Q}{A \cdot \Delta t_m} = \frac{17065}{35 \times 1.963} = 248 \text{ B/hr-ft}^2\ ^\circ\text{F}$$

$$\frac{1}{u} = \frac{1}{h_a} + \frac{(r_2 - r_1)D_2}{k_m\left(\frac{D_1 + D_2}{2}\right)} + \frac{1}{h_f}\left(\frac{D_2}{D_1}\right)$$

$k_m = 57$ B/hr-ft^2 °F (1), P. 447

$$\therefore \frac{1}{248} = \frac{1}{1738} + \frac{0.126 \times 0.753}{12 \times 57 \times \left(\frac{0.753 + 0.5}{2}\right)} + \frac{1}{h_f}\left(\frac{0.753}{0.50}\right)$$

(1), P. 6

$$0.00403 = 0.000576 + 0.0002215 + \frac{1}{h_f} \cdot \frac{1}{0.665}$$

$$\therefore \frac{1}{h_f \times 0.665} = 0.003232$$

$$\therefore h_f = \frac{1}{0.665 \times 0.003232} = 465 \text{ B/hr-ft}^2 \text{ F}$$

4. To calculate the pressure drop through annular space.

Area of the annular space = 0.000508 ft^2

$$\text{Hydraulic radius} = r_h = \frac{\frac{\pi}{4}(0.812 - 0.753)(0.812 + 0.753)}{\pi\ (0.812 + 0.753)}$$

$$= \frac{0.812 - 0.753}{4} = 0.01475 \text{ in} = 0.00123 \text{ ft}$$

Total heat input in the boiler = 5 kw = 17065 B/hr

Temperature rise of water = 30° F

Weight rate of water flow = M = 569 lb/hr

$$= \frac{569}{3600 \times 62.4} = 0.002535 \text{ cu ft}$$

$\therefore$ Velocity of the water in annular space $= \dfrac{0.002535}{0.000508}$

$= 4.99$ ft/sec

From (2), Re = 2325

f = 0.01

$$\frac{\Delta P}{L} = f \frac{V^2}{2\,g_c} \cdot \frac{1}{r_h} = 0.01 \times \frac{62.4 \times (4.99)^2}{64.4 \times 0.00123}$$

$$= 196 \frac{PS_f}{ft} = 1.36 \text{ psi/ft}$$

5. To calculate the flow rate of Freon-12 with maximum power input.

Assume maximum power input = 5 kw = 17065 B/hr

(a) Assume Freon-12 vapor at 70° F and 84.82 psia

h_g = 85.82 B/lb $v_g = 0.493$ ft^3/lb   (Air Condition-

h_f = 23.9 B/lb $v_f = 0.014$ ft^3/lb   ing-Refrigerating

h_{fg} = 85.82 - 23.90 = 61.93 B/lb   Data Book.)

Mass flow rate of Freon-12 $= \dfrac{17065}{61.92 \times 60} = 4.6 \dfrac{lb}{min}$

$= 275.5$ lb/hr

Vapor velocity in test section, assuming completely filled.

Area of cross section of inner tube $= \dfrac{\pi}{4}\left(\dfrac{0.5}{12}\right)^2 = \dfrac{0.1962}{144}$ ft^2

Freon-12 vapor velocity $= \dfrac{4.6 \times 0.493 \times 144}{0.1962} = 1665$ ft/min

$= 27.7$ ft/sec

Freon-12 (liquid) flow rate $= \dfrac{4.6 \times 0.0121}{0.1337} = 0.416$ gal/min

(b) Assume Freon-12 vapor at 100° F and 131.6 psia.

h_g = 88.62 B/lb v_g = 0.319 ft^3/lb

h_f = 31.16 B/lb v_f = 0.0127 ft^3/lb

h_{fg} = 88.62 - 31.16 = 57.46 B/lb

Mass flow rate of Freon-12 = $\frac{17065}{57.46 \times 60}$ = 4.95 lb/min

= 297 lb/hr

Freon-12 vapor velocity = $\frac{4.95 \times 0.319 \times 144}{0.1962}$ = 1159 ft/min

= 19.3 ft/sec

Freon-12 (liquid) flow rate = $\frac{4.95 \times 0.0127}{0.1337}$ = 0.471 gal/min

6. To calculate Freon-12 vapor pressure drop in test section.

(a) Assume Freon-12 vapor at 70° F

μ = 0.0123 centipoise (1), P. 468

ρ = 2.03 lb/ft^3 (Air Conditioning-Refrigerating Data Book)

$$D = \frac{1}{2 \times 12} = 0.0416 \text{ ft}$$

V = 27.7 ft/sec 5(a)

$$Re = \frac{\rho D V}{\mu} = \frac{2.03 \times 0.0416 \times 27.7}{0.0123 \times 0.000672} = 283{,}000$$

f = 0.0036

Hydraulic radius = $r_h = \frac{D_1}{4} = \frac{0.5}{4 \times 12} = 0.0104$ ft

$$\frac{\Delta P}{L} = f \frac{\rho V^2}{2 g_c} \cdot \frac{1}{r_h}$$

$$= 0.0036 \frac{2.03 \times (27.7)^2}{64.4} \times \frac{1}{0.0104} = 8.38 \text{ psf/ft}$$

$$= 0.0582 \text{ psi/ft}$$

(b) Assume Freon-12 vapor at 100° F

μ = 0.0128 centipoise (1), P. 468

ρ = 3.135 lb/ft^3 (Air Conditioning-Refrigeration Data Book)

V = 19.3 ft/sec 5(b)

$$Re = \frac{\rho DV}{\mu} = \frac{3.135 \times 0.0416 \times 19.3}{0.0128 \times 0.000672} = 292,000$$

f = 0.0037

$$\frac{\Delta P}{L} = 0.0037 \times \frac{3.135 \times (19.3)^2}{64.4 \times 0.0104}$$

$$= 6.45 \text{ psf/ft} = 0.0448 \text{ psi/ft}$$

7. To calculate Freon-12 liquid pressure drop.

Assume Freon-12 liquid at 70° F

ρ = 82.6 lb/ft^3 (Air Conditioning-Refrigerating Data Book)

μ = 0.27 C P (1), P. 484

Flow rate = 0.416 gpm 5(a)

= 0.000928 cu ft/sec

$$\text{Velocity of liquid Freon-12} = \frac{0.000928 \times 144}{0.1962}$$

$$= 0.681 \text{ ft/sec}$$

$$Re = \frac{\rho DV}{\mu} = \frac{82.6 \times 0.0416 \times 0.681}{0.000672 \times 0.27} = 12,900$$

f = 0.0071

$$\frac{\Delta P}{L} = f \frac{\rho V^2}{2 g_c r_h} = 0.0071 \times \frac{82.6 \times (0.681)^2}{64.4 \times 0.0104}$$

$$= 0.407 \text{ psf/ft} = 0.002825 \text{ psi/ft}$$

Pressure of liquid Freon-12 per foot height

$$= \frac{82.6}{144} = 0.573 \text{ psi}$$

8. To find net available volume in boiler.

Volume of the boiler:

Internal length $= 22.5 - 2 \times \frac{1}{2} + 2 \times 0.028$

$= 21.556$ inches

Internal diameter $= 6 \frac{1}{32}$ in $= 6.031$ inches

Gross volume of boiler $= 0.785\ (6.031)^2 \times 21.556$

$= 616\ in^3$

$= 0.357\ ft^3$

$= 2.665$ gallons

Added volume due to threaded hole to take heater base

$= \frac{15}{16} \times 0.785 \times (2.1875)^2 = 3.52\ in^3$

Volume occupied by heating element:

Approximate length of element = 64 inches

Outside diameter of element = 0.5 inch

Surface area of the heating element $= \pi \times \frac{1}{2} \times 64$

$= 100.5\ inches^2$

$= 0.698\ foot^2$

Volume of heating element $= 64 \times 0.785 \times (\frac{1}{2})^2$

$= 12.57\ inches^3$

$= 0.00728\ foot^3$

$= 0.0544$ gallon

Net available volume = (616 + 3.52 + 12.57)

$= 606.95 \text{ inches}^3$

$= 0.352 \text{ foot}^3$

$= 2.63$ gallons

APPENDIX C

Table 1. Experimental data of condensation of Freon-12 inside a single horizontal tube.

Run No.	Room temp. °F.	Baro. pres. in.Hg.	Freon-12 rate of flow gpm	Power input to boiler: k-watts	Power input to boiler: B/hr	Pressure: Boiler psig	Pressure: Line psig	Temperature in condenser: Freon-12 Inlet °F.	Temperature in condenser: Freon-12 Outlet °F.	Temperature in condenser: Cooling water Inlet °F.	Temperature in condenser: Cooling water Outlet °F.	Rate of cooling water lbs/hr	Temperature difference of cooling water in test section: B - A °F.	C - B °F.	D - C °F.	E - D °F.	Total (E - A) °F.	Position of the pipe	Temperature of pipe wall in test section: 1 °F.	2 °F.	3 °F.	4 °F.	5 °F.
1	82.5	--	0.28	1.6	5460	98	94	82.9	79.5	64.8	69.0	945	0.0	0.2	1.0	0.5	1.7	1	68.5	68.5	67.6	65.8	66.8
2	80.5	--	0.23	1.6	5460	97	94	82.3	79.2	64.5	69.5	890	0.3	0.4	0.2	1.4	2.3	1	67.8	67.8	66.5	65.4	66.0
3	78.0	--	0.35	2.0	6826	120	117	94.0	89.4	64.5	79.3	385	1.2	1.3	1.3	1.3	5.1	1	74.1	73.9	73.0	69.5	72.2
4	76.0	--	0.45	2.4	8190	141	138	104.2	88.4	63.5	81.0	372	1.4	1.7	1.2	1.6	5.9	1	76.2	76.1	76.1	69.9	75.0
5	78.5	--	0.42	2.4	8190	136	133	101.2	91.2	62.9	80.9	366	2.1	1.9	1.6	1.8	5.4	1	76.0	75.1	75.1	68.8	73.5
6	67.5	--	0.23	2.8	9556	112	109	88.9	87.2	60.0	69.7	740	0.5	1.1	1.3	1.2	4.1	1	64.0	64.0	62.0	59.0	61.1
7	75.0	--	0.23	2.74	9352	116	112	92.2	90.8	63.7	74.3	634	1.364	0.955	0.818	0.591	3.728	1	67.5	67.4	65.4	64.2	64.8
8	78.0	--	0.23	2.8	9556	120	116	94.9	93.2	65.1	75.9	643	1.272	1.045	0.818	0.591	3.726	1	73.5	72.7	70.8	68.5	71.0
9	78.0	--	0.23	2.8	9556	120	118	97.6	95.7	67.0	78.3	610	0.955	1.364	0.409	0.955	3.683	1	71.9	71.8	69.9	67.0	68.0
10	77.0	--	0.23	2.8	9556	120	117	96.1	94.7	66.0	77.0	610	1.09	1.228	0.500	0.955	3.773	1	71.0	70.8	69.9	67.0	68.2
11	75.5	--	0.23	2.8	9556	117	114	96.0	94.7	67.0	77.9	610	0.682	1.50	0.728	0.955	3.865	1	72.7	71.9	70.0	67.4	69.0
12	76.0	--	0.23	2.8	9556	120	117	96.0	94.2	65.8	77.0	610	0.682	1.50	0.728	0.955	3.865	1	72.0	71.8	70.0	67.4	69.5
13	77.0	--	0.27	3.2	10922	130	126	101.0	98.8	67.0	79.8	617	1.047	1.590	0.591	1.230	4.458	1	71.9	71.9	69.3	67.6	69.0
14	77.0	--	0.27	3.14	10717	128	125	100.8	98.2	67.1	79.9	617	0.864	1.50	0.591	1.230	4.185	1	71.0	71.0	69.4	66.5	68.5
15	76.0	--	0.275	3.2	10922	130	127	100.7	98.1	66.0	78.9	614	1.09	1.50	0.591	1.230	4.411	1	71.8	71.0	69.2	65.6	69.0
16	76.0	--	0.275	3.2	10922	130	127	100.0	98.0	66.0	78.7	614	0.816	1.50	0.591	1.230	4.140	1	70.8	70.6	68.7	65.4	69.0
17	77.0	--	0.275	3.2	10922	130	126	99.9	97.8	65.9	78.2	628	0.96	1.325	0.640	1.10	4.025	1	70.7	70.7	68.7	65.2	68.0
18	76.0	--	0.275	3.2	10922	128	125	98.0	96.2	64.2	76.8	628	0.915	1.37	0.640	1.10	4.025	1	70.0	69.9	67.3	65.3	67.6
19	76.5	--	0.275	3.2	10922	128	125	99.4	97.3	65.2	77.9	614	0.727	1.228	1.137	1.09	4.182	1	69.9	69.2	67.7	65.2	66.9
20	76.5	--	0.275	3.2	10922	129	125	99.3	97.4	65.0	78.0	614	0.864	1.362	0.818	1.41	4.454	1	69.9	69.3	67.7	65.2	66.9
21	76.0	--	0.305	3.6	12287	141	137	105.0	101.3	59.0	76.4	606	1.000	1.78	1.047	1.362	5.189	1	71.9	71.5	69.6	66.4	69.0
22	80.5	--	0.26	3.012	10280	122	--	95.4	90.5	62.0	70.2	600	1.545	1.363	0.864	1.000	4.772	1	69.2	68.6	67.4	64.8	66.0
23	77.0	28.90	0.26	3.06	10440	123	--	94.6	90.0	60.8	68.5	620	1.453	1.228	0.955	0.955	4.591	1	67.4	67.2	65.5	62.0	64.0
24	74.0	29.08	0.29	3.68	12580	134	134	100.0	94.5	56.2	74.3	628	1.546	1.590	1.000	1.410	5.546	1	67.5	66.5	64.3	62.0	64.2
25	76.0	29.05	0.29	3.52	12000	132	132	98.8	94.4	58.0	75.4	644	1.590	1.546	1.000	1.272	5.408	1	68.6	67.5	65.7	63.2	64.9
26	80.0	28.92	0.29	3.52	12000	126	126	96.1	91.1	57.1	71.0	825	1.319	1.319	0.864	0.455	3.957	1	66.7	66.6	64.5	62.1	63.8
27	79.0	28.92	0.295	3.66	12500	137	137	99.1	94.0	57.9	75.9	640	1.681	1.681	1.181	0.864	5.407	1	69.3	68.3	66.6	63.1	65.8
28	80.0	28.83	0.295	3.64	12420	139	139	101.1	95.5	57.9	76.2	631	1.729	1.638	1.045	0.592	5.004	1	69.3	68.6	66.7	64.2	66.0
29	79.0	28.92	0.295	3.58	12210	138	138	100.6	97.0	58.2	76.1	621	1.729	1.772	0.864	0.592	4.957	1	70.0	69.8	67.5	60.3	66.6
30	79.0	28.67	0.30	3.672	12520	142	142	102.5	98.2	58.5	77.6	600	1.368	1.820	1.000	0.773	4.961	1	71.5	70.9	68.6	65.6	66.4
31	84.0	28.48	0.46	4.08	13900	183	183	120.0	94.4	61.2	81.9	631	1.862	2.140	0.955	1.000	5.957	1	78.1	78.0	75.8	70.7	74.0
32	82.0	28.89	0.45	4.0	13650	177	177	113.9	92.3	59.1	80.1	585	2.228	1.820	1.138	0.774	5.96	1	74.0	73.8	71.0	65.6	69.3
33	85.0	28.83	0.45	4.04	13800	182	182	117.9	92.1	60.5	81.0	630	2.183	2.045	1.138	0.774	6.14	1	75.3	75.3	72.0	67.5	71.1
34	85.0	28.53	0.44	4.02	13720	179	179	117.3	92.1	60.6	81.0	631	1.820	2.180	1.000	0.910	5.91	1	76.9	76.4	73.9	72.9	69.1
35	76.5	--	0.275	3.20	10922	128	125	99.4	97.3	65.2	77.9	614	0.727	1.228	1.137	1.090	4.182	1	69.9	69.2	67.7	65.2	66.9

Table 1 (cont.)

Run No.	Room temp. °F.	Baro. pres. in. Hg.	Freon-12 rate of flow gpm	Power input to boiler: k-watts	Power input to boiler: B/hr	Pressure: Boiler psig	Pressure: Line psig	Temperature in condenser, Freon-12: Inlet °F.	Freon-12: Outlet °F.	Cooling water: Inlet °F.	Cooling water: Outlet °F.	Rate of cooling water lbs/hr	Temperature difference of cooling water in test section: B - A °F.	C - B °F.	D - C °F.	E - D °F.	Total (E - A) °F.	Position of the pipe	Temperature of pipe wall in test section: 1 °F.	2 °F.	3 °F.	4 °F.	5 °F.
36	79.0	28.83	0.295	3.54	12090	135	135	99.9	95.0	57.9	75.9	631	1.729	1.681	1.000	0.592	5.002	1	69.3	68.6	66.7	64.2	66.0
37	79.0	28.92	0.295	3.60	12290	138	138	100.6	96.9	57.8	76.1	621	1.729	1.772	0.864	0.592	4.957	1	70.0	69.9	67.6	60.4	66.7
38	80.0	28.83	0.295	3.60	12290	139	139	102.5	98.8	56.5	77.6	600	1.772	1.772	1.000	0.819	5.313	1	70.5	70.1	67.8	65.0	66.9
39	79.5	28.67	0.30	3.62	12350	141	141	102.5	98.9	58.5	77.6	590	1.729	1.955	0.864	0.773	5.321	1	71.5	71.0	69.0	66.4	68.0
40	84.5	28.48	0.46	4.00	13650	176	177	118.0	92.9	61.1	79.5	694	1.638	1.772	0.910	1.000	5.320	1	76.0	75.9	72.8	68.6	71.2
41	81.0	28.89	0.46	4.00	13650	176	176	115.0	93.0	60.1	80.6	615	2.000	1.910	1.000	0.910	5.82	1	75.0	74.0	71.9	67.5	71.0
42	85.0	28.83	0.45	3.94	13450	173	173	114.0	92.1	60.0	79.6	631	2.000	1.820	1.091	0.637	5.548	1	74.0	73.9	71.0	66.7	69.4
43	73.0	29.22	0.41	3.68	12950	154	152	105.8	75.1	58.2	75.4	590	1.410	1.863	1.091	2.045	6.409	2	70.7	70.6	67.5	65.1	66.0
44	72.0	28.97	0.24	2.84	9700	131	132	95.0	88.0	58.1	81.2	403	2.410	1.681	0.865	2.364	7.320	2	72.5	71.9	69.4	69.7	69.0
45	74.5	28.83	0.42	3.64	12420	158	156	107.8	78.3	58.1	80.2	554	2.273	2.590	0.955	2.275	8.093	2	74.0	73.8	70.6	69.7	69.8
46	73.0	28.88	0.47	4.16	14200	201	200	124.2	78.2	58.2	82.6	569	2.320	2.955	1.319	2.728	9.322	2	75.1	74.5	71.1	63.4	70.8
47	72.0	28.97	0.38	3.22	11000	135	134	98.2	86.7	58.8	78.1	554	2.000	2.225	0.591	1.728	6.544	2	71.1	70.1	67.8	67.8	66.8
48	68.0	29.28	0.22	2.64	9010	116	117	90.7	83.7	58.8	74.9	530	1.730	1.545	0.591	1.455	5.321	2	68.0	67.5	64.5	64.1	64.0
49	66.0	29.27	0.36	3.2	10920	132	132	98.1	86.7	58.2	77.9	542	2.138	1.955	0.910	1.319	6.322	2	70.2	69.1	66.0	66.0	65.3
50	66.0	29.29	0.23	2.76	9420	116	116	87.8	81.5	56.5	73.2	550	2.000	1.410	0.409	1.455	5.274	2	65.0	64.2	62.1	62.0	61.8
51	70.0	29.28	0.38	3.18	10880	129	128	93.4	83.6	56.9	75.9	559	2.545	1.090	0.728	2.362	6.725	2	67.7	67.5	65.0	65.1	64.5
52	71.5	29.32	0.40	3.64	12420	152	151	103.8	73.7	53.5	76.0	540	2.862	1.863	0.909	3.180	8.814	2	69.7	69.0	66.3	64.31	65.5
53	67.0	29.34	0.46	4.1	14000	194	191	121.7	77.2	57.2	82.2	540	2.500	3.320	1.272	2.229	9.321	2	73.1	72.5	69.7	61.9	69.1
54	69.0	29.47	0.32	2.96	10110	121	121	89.8	82.0	56.8	74.8	550	2.275	1.455	0.409	1.771	5.910	2	66.9	66.3	64.6	64.0	63.1
55	70.0	29.44	0.37	3.4	11610	140	139	98.5	78.0	56.8	77.0	559	2.590	1.410	0.636	2.680	7.316	2	70.0	69.7	66.9	66.7	66.0
56	72.0	29.58	0.45	3.88	13280	175	174	113.0	77.0	57.7	82.2	526	2.910	2.410	1.090	3.140	9,550	2	74.0	74.0	71.0	67.0	69.8
57	71.0	29.51	0.29	2.87	9800	119	119	88.7	81.6	57.0	74.0	554	1.955	1.229	0.500	2.320	6.004	2	66.3	65.7	63.3	64.1	63.2
58	71.5	29.35	0.38	3.14	10720	127	127	92.2	83.7	57.0	75.5	563	2.545	1.046	0.636	2.545	6.772	2	67.5	66.9	64.5	64.2	63.9
59	72.0	29.22	0.40	3.74	12790	161	159	107.8	76.2	56.8	80.0	534	2.820	2.092	1.181	2.775	8.868	2	72.3	71.9	69.8	66.7	68.9
60	72.0	28.93	0.36	3.02	10310	125	125	91.6	83.8	57.2	66.8	555	2.590	1.000	0.955	1.775	6.320	2	68.0	67.7	65.4	65.4	64.9
61	74.5	28.82	0.38	3.04	10390	128	128	93.1	84.0	58.1	75.5	576	0.910	1.863	0.865	0.546	4.184	3	73.0	71.9	68.9	68.9	67.7
62	76.5	28.71	0.44	3.24	11070	135	135	97.0	85.8	59.0	78.0	567	1.228	0.910	0.910	0.910	3.958	3	71.8	71.0	67.6	67.6	66.8
63	76.5	28.71	0.47	3.84	13100	174	174	113.2	79.5	59.7	82.2	563	1.863	2.363	1.319	1.319	6.864	3	74.0	73.9	69.9	67.3	69.3
64	73.0	29.11	0.38	3.00	10230	126	126	92.5	83.4	58.0	76.1	545	1.500	1.544	0.818	0.455	4.317	3	68.2	67.6	64.9	65.0	64.0
65	74.0	29.11	0.46	3.52	12010	149	148	102.2	79.4	58.1	78.9	567	1.820	1.863	0.865	1.319	5.867	3	70.0	70.0	66.4	65.7	66.5
66	73.0	29.11	0.48	3.74	12780	165	164	113.0	79.4	59.0	81.8	545	1.500	2.830	1.137	0.955	6.422	3	72.5	72.5	68.8	66.4	68.0
67	73.0	29.32	0.25	2.78	9500	121	121	89.9	82.5	58.1	74.7	558	1.000	1.820	0.409	0.865	4.094	3	67.0	66.5	63.5	63.7	63.0
68	74.0	29.32	0.44	3.56	12170	154	154	105.7	81.4	59.7	82.1	526	1.590	2.590	0.910	0.865	5.955	3	73.0	72.4	69.0	68.0	68.1
69	72.5	28.98	0.25	2.87	9800	125	125	93.1	84.8	59.1	76.0	572	0.910	1.910	0.773	0.865	4.458	3	69.2	68.8	65.5	65.0	65.0
70	74.5	28.67	0.23	2,76	9420	124	124	91.1	85.0	59.1	76.0	567	1.090	1.319	0.500	1.730	4.639	3	69.1	68.7	65.7	65.7	65.3

Table 1 (cont.)

Run No.	Room temp. °F.	Baro. pres. in.Hg.	Freon-12 rate of flow gpm	Power input to boiler: k-watts	Power input to boiler: B/hr	Pressure: Boiler psig	Pressure: Line psig	Temperature in condenser: Freon-12 Inlet ° F.	Freon-12 Outlet ° F.	Cooling water Inlet ° F.	Cooling water Outlet ° F.	Rate of cooling water lbs/hr	Temperature difference of cooling water in test section: B - A ° F.	C - B ° F.	D - C ° F.	E - D ° F.	Total (E - A) ° F.	Position of the pipe	Temperature of pipe wall in test section: 1 ° F.	2 ° F.	3 ° F.	4 ° F.	5 ° F.
71	78.0	28.56	0.45	3.62	12380	161	160	108.9	83.4	60.2	83.8	576	2.090	2.044	1.000	1.772	6.906	3	75.5	75.2	71.5	70.0	70.9
72	77.0	28.56	0.47	4.04	13800	193	192	118.8	82.7	60.9	86.9	518	2.363	2.590	1.181	2.137	8.271	3	78.0	77.9	73.0	69.0	72.8
73	78.5	28.55	0.23	2.76	9420	126	126	93.8	80.7	59.8	77.9	528	0.955	1.272	0.500	1.863	4.590	3	70.7	70.1	67.4	67.3	66.9
74	77.0	28.57	0.44	3.56	12170	153	152	106.4	82.7	60.1	81.9	558	1.820	1.953	0.955	1.863	6.591	3	74.8	74.5	70.8	69.7	70.0
75	77.0	29.25	0.21	2.64	9010	117	118	90.2	83.8	58.8	74.6	554	1.000	1.272	0.546	1.680	4.498	3	68.8	68.2	65.4	65.6	65.1
76	77.5	29.31	0.37	3.22	11000	134	134	96.4	86.0	58.1	77.2	554	1.500	1.454	0.591	2.090	5.635	3	69.9	69.8	66.4	66.5	66.0
77	77.0	29.32	0.41	3.76	12830	164	164	111.0	81.2	59.5	82.1	538	2.000	2.000	1.228	1.863	7.091	3	74.8	74.5	70.2	69.3	69.9
78	70.0	29.33	0.43	3.48	11890	147	146	104.0	81.9	58.1	80.0	529	1.820	2.320	0.865	1.364	6.369	3	71.9	71.7	67.7	67.6	67.3
79	68.0	29.34	0.21	2.76	9420	119	119	89.3	82.3	57.7	74.0	563	1.047	1.547	0.682	0.955	4.231	3	66.9	67.0	64.0	64.0	63.3
80	75.0	28.73	0.39	3.32	11330	135	135	97.0	80.5	56.8	75.9	573	1.047	1.362	0.364	0.955	3.728	4	73.8	73.8	70.0	70.6	69.0
81	76.0	28.68	0.41	3.60	12300	153	152	104.3	77.8	58.0	78.0	600	1.000	1.730	0.318	1.090	4.138	4	75.1	75.9	72.0	71.1	71.1
82	77.0	28.67	0.43	3.92	13390	178	176	115.0	78.9	58.0	81.8	560	1.000	1.865	0.545	1.682	5.092	4	78.2	78.9	75.0	72.0	74.2
83	75.0	28.51	0.27	2.84	9700	121	121	91.3	85.0	57.4	74.6	549	0.545	1.271	0.1364	1.271	3.2234	4	73.4	73.0	70.7	71.3	70.3
84	76.0	28.73	0.36	3.24	11080	135	135	99.0	87.9	57.7	77.9	536	1.181	1.319	0.091	1.410	4.001	4	76.1	76.0	73.0	73.7	73.0
85	77.0	29.23	0.42	3.82	13050	169	168	112.6	77.8	57.7	79.3	540	1.090	1.865	0.273	2.000	5.228	4	77.2	76.8	72.5	70.7	72.8
86	77.0	29.42	0.47	4.22	14410	208	207	126.3	80.6	58.0	84.2	537	1.500	2.137	0.364	2.000	6.001	4	79.5	79.3	74.2	71.0	74.2
87	76.0	29.33	0.245	2.80	9560	121	121	91.4	85.2	56.8	74.6	531	0.727	1.900	0.091	1.410	4.128	4	72.4	72.0	70.0	71.0	69.5
88	77.5	29.21	0.38	3.20	10930	133	132	97.4	87.8	57.2	77.0	542	1.047	1.181	0.2275	1.453	3.9085	4	74.3	73.9	71.3	71.9	70.7
89	78.0	29.20	0.40	3.58	12220	152	151	105.8	81.0	58.0	79.5	545	1.047	1.500	0.273	1.820	4.640	4	77.0	76.8	73.4	72.9	72.9
90	75.5	29.25	0.46	4.04	13800	190	189	115.8	80.1	58.2	83.9	545	1.410	2.225	0.1364	2.180	5.9514	4	78.6	78.2	74.0	71.8	73.8
91	76.0	28.83	0.22	2.64	9020	118	118	90.0	84.4	57.7	74.0	539	0.865	0.910	0.2275	1.090	3.0925	4	70.7	70.7	68.2	69.0	67.5
92	79.0	28.73	0.36	2.98	10180	128	128	95.1	87.8	58.7	77.9	522	0.681	1.138	0.0455	1.410	3.2745	4	73.4	73.0	70.2	71.3	69.5
93	79.0	28.66	0.41	3.44	11750	151	150	105.0	83.1	58.1	80.8	516	1.227	1.453	0.0455	1.453	4.1785	4	76.0	76.0	72.2	72.3	71.5
94	77.0	28.71	0.27	2.84	9750	121	121	90.9	84.9	57.7	74.6	554	0.819	0.865	0.1364	1.319	3.1394	4	69.9	69.8	67.3	67.7	66.0
95	79.5	28.72	0.40	3.20	10920	133	131	96.8	87.9	57.2	76.9	545	0.681	1.138	0.273	1.453	3.545	4	70.8	70.7	67.9	68.2	66.9
96	76.0	28.92	0.44	3.92	13400	176	175	115.2	80.3	57.7	81.9	540	1.362	2.090	0.1364	1.773	5.3614	4	74.8	74.2	70.7	67.8	69.5
97	74.0	29.21	0.41	3.24	11080	134	133	97.0	86.9	56.8	76.1	550	1.319	0.318	0.455	1.410	3.502	4	69.3	69.3	66.2	66.8	65.8
98	76.0	29.29	0.43	3.54	12100	150	149	104.0	80.4	56.8	79.0	530	1.453	1.047	0.318	1.410	4.228	4	72.3	72.0	69.0	68.9	68.0
99	75.0	29.40	0.46	4.24	14500	204	203	126.3	80.0	56.8	84.4	520	1.820	1.820	0.500	2.225	6.365	4	75.0	74.9	70.0	67.4	69.3
100	72.5	29.36	0.43	3.62	12380	153	151	105.0	79.2	56.2	78.9	531	2.275	1.047	0.2275	0.955	4.5045	4	71.4	71.0	67.7	67.5	66.9
101	81.5	29.19	0.43	3.98	13600	168	168	113.0	87.3	61.8	82.8	600	1.455	1.863	1.364	0.819	5.501	5	75.3	75.2	71.5	71.0	71.2
102	82.0	29.16	0.43	4.00	13650	169	169	115.1	86.0	61.9	82.0	632	2.180	1.863	1.620	1.41	7.473	5	76.0	76.0	71.9	69.8	71.5
103	86.0	28.87	0.43	4.12	14100	181	181	120.2	90.0	63.2	84.5	620	3.136	1.681	0.727	1.773	7.317	5	76.5	76.5	75.0	73.9	75.2
104	85.0	28.84	0.42	3.98	13600	170	170	114.0	89.2	61.8	82.5	615	1.410	1.681	0.727	1.272	5.090	5	76.9	76.7	72.9	71.9	72.9
105	84.0	29.08	0.42	3.96	13520	166	166	113.0	85.9	60.9	81.5	620	1.820	2.093	0.910	1.320	6.143	5	75.1	75.0	71.8	69.7	71.2

Table 1 (concl.).

Run No.	Room temp. °F.	Baro. pres. in.Hg.	Freon-12 rate of flow gpm	Power input to boiler: k-watts	Power input to boiler: B/hr	Pressure: Boiler psig	Pressure: Line psig	Temperature in condenser, Freon-12: Inlet °F.	Temperature in condenser, Freon-12: Outlet °F.	Temperature in condenser, Cooling water: Inlet °F.	Temperature in condenser, Cooling water: Outlet °F.	Rate of cooling water lbs/hr	Temperature difference of cooling water in test section: B - A °F.	C - B °F.	D - C °F.	E - D °F.	Total (E - A) °F.	Position of the pipe	Temperature of pipe wall in test section: 1 °F.	2 °F.	3 °F.	4 °F.	5 °F.
106	84.0	29.08	0.43	4.14	14150	178	178	116.9	87.0	61.6	83.1	620	1.182	1.269	1.320	0.910	4.681	5	85.3	84.6	76.5	76.4	75.4
107	84.0	29.09	0.42	3.98	13600	168	168	111.9	86.0	61.0	81.3	621	1.000	1.728	1.047	0.455	4.230	5	77.1	76.8	72.9	75.5	72.6
108	77.0	28.82	0.43	4.00	13650	181	181	105.8	82.9	61.7	82.0	648	1.272	1.955	0.819	0.955	5.001	5	75.0	74.3	69.8	68.9	70.4
109	--	28.96	0.43	3.98	13600	180	180	107.4	82.3	61.9	82.9	631	1.000	2.500	1.047	0.955	5.502	5	75.2	75.0	71.2	69.4	71.0
110	77.0	28.98	0.43	3.98	13600	181	181	107.0	82.9	61.7	82.6	630	1.138	2.225	0.819	0.955	5.137	5	76.0	75.9	71.5	69.4	71.5
111	82.0	28.95	0.40	3.54	12100	159	159	108.5	90.8	61.7	84.3	629	0.774	1.590	0.865	0.865	4.094	5	76.0	75.9	72.4	72.5	72.2
112	80.0	28.93	0.39	3.56	12150	159	159	108.5	91.1	62.0	84.4	532	0.910	1.820	0.729	0.691	4.150	5	77.0	76.5	73.0	73.3	73.0
113	82.0	28.83	0.40	3.60	12290	161	160	109.6	88.8	61.3	84.3	533	0.910	1.955	0.455	0.865	4.185	5	77.0	76.9	73.0	73.0	72.7
114	80.0	28.74	0.26	3.00	10250	137	136	100.3	91.7	61.8	80.2	533	0.910	1.410	0.500	0.910	3.730	5	74.9	74.1	71.7	72.4	70.9
115	80.0	28.83	0.35	3.20	10920	142	142	102.1	91.4	61.5	81.7	533	0.819	1.683	0.364	1.091	3.957	5	75.3	75.1	72.5	73.1	72.1
116	80.0	28.83	0.35	3.20	10920	142	142	102.1	91.3	61.4	81.8	533	0.819	1.680	0.364	1.091	3.954	5	75.2	75.0	72.5	73.2	72.0
117	79.0	28.76	0.39	3.62	12350	161	161	109.9	87.8	61.5	84.4	533	1.500	2.181	0.546	1.319	5.546	5	78.1	77.4	73.9	73.9	73.2
118	84.0	29.02	0.40	3.60	12290	164	164	111.7	86.9	63.1	83.6	598	1.181	1.544	0.546	0.865	4.136	5	77.3	77.1	73.9	73.3	73.2
119	90.0	28.94	0.41	3.72	12700	175	174	116.6	89.0	63.2	85.9	563	1.271	1.544	0.546	1.138	4.499	5	80.2	80.1	76.9	76.1	77.1
120	92.0	28.85	0.41	3.70	12620	173	173	117.4	90.4	63.2	86.1	550	1.544	1.410	0.3185	1.500	4.773	5	81.3	81.1	77.3	77.1	78.1
121	93.0	28.92	0.41	3.70	12620	174	174	118.4	92.2	64.2	87.3	546	1.680	1.362	0.409	1.453	4.603	5	81.7	81.4	77.4	77.3	78.2
122	90.0	28.91	0.41	3.76	12820	179	179	118.1	93.8	66.2	89.9	540	1.453	1.319	0.455	1.410	4.637	5	83.6	82.9	79.1	78.6	80.1
123	87.0	28.92	0.41	3.68	12580	172	171	115.1	91.4	64.1	87.8	530	1.410	1.453	0.455	1.319	4.637	5	81.1	80.2	77.0	77.0	77.5
124	90.0	28.69	0.42	3.81	12990	184	184	121.3	92.1	65.0	90.1	516	1.590	1.500	0.409	1.729	5.228	5	83.6	82.9	79.1	78.3	80.8
125	88.0	28.81	0.42	3.90	13310	186	185	120.6	89.2	64.2	88.2	552	1.500	1.729	0.455	1.410	5.094	5	81.5	81.1	77.3	76.8	78.0
126	81.0	29.04	0.41	3.72	12700	171	171	114.0	89.0	63.5	86.2	558	1.680	1.362	0.546	1.319	4.907	5	78.6	78.0	74.2	73.9	75.2
127	75.0	29.04	0.40	3.68	12580	166	165	110.2	86.0	61.3	84.2	537	0.682	1.772	0.546	1.271	4.271	5	76.9	76.0	72.4	71.8	72.0
128	79.0	28.91	0.41	3.80	12980	179	178	116.1	86.1	63.3	85.7	571	1.544	1.453	0.500	1.319	4.816	5	78.1	77.3	73.8	72.3	73.1
129	79.5	28.91	0.41	3.74	12760	184	184	117.5	91.5	62.9	92.3	437	1.544	1.953	0.364	1.544	5.405	5	81.3	80.2	76.1	75.3	76.3
130	78.0	29.16	0.41	3.74	12760	173	173	114.0	86.0	62.3	84.5	571	1.958	1.000	0.455	1.319	4.727	5	77.1	76.1	72.5	71.5	72.5
131	77.5	29.27	0.40	3.72	12700	174	174	113.9	87.8	62.9	86.1	532	1.500	1.453	0.455	1.271	4.679	5	78.1	77.2	73.2	72.3	73.1
132	78.5	28.72	0.41	3.80	12980	181	181	116.6	86.9	63.9	87.4	555	1.729	1.410	0.409	1.319	4.867	5	78.9	78.2	74.2	73.0	75.2
133	81.0	28.58	0.33	3.16	10790	147	147	104.0	92.2	62.7	80.1	525	1.000	1.453	0.455	0.864	3.772	5	75.3	75.0	71.0	72.5	71.8
134	82.0	29.02	0.39	3.56	12130	164	164	110.0	89.1	61.3	85.1	511	0.727	1.590	0.772	0.909	3.998	5	76.7	76.1	72.8	73.0	72.9
135	76.0	28.96	0.38	3.32	11320	150	149	104.4	90.1	61.9	82.1	538	1.227	1.453	0.455	1.000	4.135	5	74.2	73.9	69.8	70.7	71.0
136	76.0	28.97	0.23	2.79	9530	134	134	97.9	87.9	61.0	78.5	525	0.319	1.635	0.591	0.681	3.226	5	71.9	71.5	68.7	69.5	68.3
137	77.5	28.97	0.40	3.64	12420	165	164	111.3	86.2	60.9	83.9	526	0.727	1.772	0.500	1.229	4.228	5	75.5	75.2	71.9	71.5	71.8
138	77.0	28.96	0.30	3.02	10300	137	137	99.7	88.4	60.3	78.9	552	0.455	1.590	0.636	0.546	4.227	5	72.0	71.6	68.5	69.1	68.2
139	77.5	28.96	0.43	3.84	13100	176	176	116.0	84.7	61.1	84.9	538	0.910	1.955	0.455	1.229	4.549	5	76.7	76.0	71.3	71.5	72.2
140	79.0	28.98	0.225	2.78	9490	132	131	97.9	87.9	61.1	78.0	540	0.546	1.319	0.546	0.500	3.911	5	71.5	71.1	68.5	69.0	68.1
141	81.0	28.98	0.40	3.60	12290	162	162	110.3	87.8	61.2	84.0	530	0.500	1.820	0.546	0.865	3.731	5	76.0	75.3	72.0	71.9	72.0
142	81.0	28.92	0.35	3.20	10920	144	143	102.5	89.9	60.4	80.0	556	0.500	1.544	0.455	0.772	3.271	5	73.8	73.1	69.8	69.9	69.9

APPENDIX D

Table 2. Physical properties of liquid Freon-12. Condensation of Freon-12 inside a single horizontal tube.

Run No.	Average bulk temperature of Freon-12 °F	Density ρ lb/ft^3	Viscosity μ centipoise	Specific heat C_{p_f} B/lb °F	Thermal conductivity k_b B/hr-ft-°F
1	81.20	81.3	0.255	0.255	0.0518
2	80.75	81.3	0.255	0.255	0.0520
3	91.70	80.0	0.250	0.265	0.0491
4	96.30	79.4	0.242	0.266	0.0485
5	96.15	79.4	0.242	0.266	0.0485
6	88.05	80.6	0.251	0.264	0.0495
7	91.50	80.0	0.250	0.265	0.0491
8	94.05	79.4	0.245	0.265	0.0488
9	96.65	79.4	0.242	0.266	0.0484
10	97.4	79.4	0.241	0.266	0.0484
11	95.35	79.4	0.245	0.266	0.0486
12	95.10	78.8	0.245	0.266	0.0486
13	99.90	79.0	0.240	0.268	0.0480
14	99.50	79.0	0.240	0.268	0.0481
15	99.40	79.1	0.240	0.268	0.0481
16	99.00	79.1	0.240	0.268	0.0481
17	98.85	79.4	0.240	0.267	0.0482
18	97.10	79.4	0.241	0.267	0.0484
19	98.35	79.4	0.240	0.267	0.0482
20	98.35	79.4	0.240	0.267	0.0482
21	103.15	78.4	0.237	0.269	0.0476
22	92.95	79.7	0.245	0.265	0.0489
23	92.30	79.8	0.245	0.265	0.0490
24	97.25	79.4	0.241	0.267	0.0484
25	96.60	79.4	0.242	0.267	0.0485
26	93.60	79.4	0.245	0.265	0.0488
27	96.55	79.4	0.242	0.266	0.0485
28	98.30	79.4	0.240	0.267	0.0482
29	98.80	79.1	0.240	0.267	0.0482
30	100.35	78.8	0.239	0.268	0.0480
31	107.20	77.8	0.235	0.270	0.0471
32	103.10	78.4	0.237	0.269	0.0476
33	105.10	78.1	0.236	0.269	0.0474
34	104.70	78.1	0.236	0.269	0.0474
35	98.35	79.4	0.240	0.267	0.0482

Table 2 (cont.)

Run No.	Average bulk temperature of Freon-12 °F	Density ρ lb/ft^3	Viscosity μ centipoise	Specific heat C_{p_f} B/lb °F	Thermal conductivity k_b B/hr-ft-°F
36	97.45	79.4	0.240	0.267	0.0483
37	98.75	79.4	0.240	0.267	0.0482
38	100.65	78.8	0.239	0.268	0.0479
39	100.70	78.8	0.239	0.268	0.0479
40	105.45	78.1	0.236	0.269	0.0473
41	104.00	78.1	0.236	0.269	0.0475
42	103.05	78.4	0.235	0.269	0.0476
43	95.45	79.4	0.245	0.262	0.0486
44	91.50	80.0	0.247	0.261	0.0491
45	93.05	79.7	0.246	0.262	0.0489
46	101.20	78.8	0.240	0.265	0.0478
47	92.45	80.0	0.247	0.261	0.0490
48	87.20	80.6	0.250	0.260	0.0496
49	92.40	80.0	0.247	0.261	0.0488
50	84.65	80.6	0.251	0.258	0.0500
51	88.50	80.6	0.249	0.260	0.0494
52	88.75	80.3	0.249	0.260	0.0494
53	99.45	78.9	0.242	0.264	0.0481
54	85.90	80.6	0.251	0.258	0.0498
55	88.40	80.6	0.249	0.260	0.0494
56	95.00	79.4	0.245	0.263	0.0486
57	85.15	80.6	0.251	0.259	0.0499
58	87.95	80.6	0.249	0.260	0.0495
59	92.00	80.0	0.247	0.261	0.0490
60	87.70	80.6	0.249	0.260	0.0496
61	88.60	80.3	0.250	0.260	0.0495
62	91.40	80.0	0.245	0.263	0.0491
63	96.35	79.4	0.240	0.265	0.0485
64	87.95	80.6	0.250	0.260	0.0495
65	90.80	80.0	0.248	0.262	0.0492
66	96.20	79.4	0.240	0.265	0.0485
67	86.20	80.6	0.253	0.259	0.0498
68	93.55	79.4	0.243	0.264	0.0488
69	88.95	80.0	0.250	0.260	0.0494
70	88.05	80.6	0.250	0.260	0.0495

Table 2 (Cont.)

Run No.	Average bulk temperature of Freon-12 ° F	Density ρ lb/ft^3	Viscosity μ centipoise	Specific heat C_{p_f} B/lb ° F	Thermal conductivity k_b B/hr-ft-°F
71	96.15	79.4	0.240	0.265	0.0485
72	100.75	78.8	0.239	0.267	0.0479
73	90.25	80.0	0.248	0.262	0.0492
74	94.55	79.4	0.243	0.264	0.0487
75	87.00	80.6	0.252	0.259	0.0496
76	91.20	80.0	0.248	0.263	0.0491
77	96.10	79.4	0.240	0.265	0.0485
78	92.95	79.7	0.242	0.263	0.0489
79	85.80	80.6	0.254	0.258	0.0498
80	88.75	80.0	0.249	0.260	0.0494
81	91.05	80.0	0.248	0.261	0.0492
82	96.95	79.4	0.240	0.265	0.0484
83	88.15	80.0	0.249	0.260	0.0495
84	93.45	79.6	0.246	0.262	0.0488
85	95.20	79.4	0.245	0.262	0.0486
86	103.45	78.2	0.237	0.269	0.0475
87	88.30	80.0	0.249	0.260	0.0485
88	92.60	79.7	0.247	0.261	0.0489
89	93.40	79.4	0.246	0.262	0.0488
90	97.95	81.3	0.240	0.267	0.0505
91	87.20	80.6	0.250	0.260	0.0496
92	91.45	80.0	0.247	0.261	0.0491
93	94.05	79.4	0.243	0.264	0.0488
94	87.90	80.6	0.250	0.260	0.0495
95	92.35	80.0	0.247	0.261	0.0490
96	97.75	79.4	0.240	0.267	0.0483
97	91.95	80.0	0.245	0.263	0.0490
98	92.20	80.0	0.247	0.261	0.0490
99	103.15	78.4	0.237	0.269	0.0475
100	92.10	80.0	0.247	0.261	0.0490
101	100.15	78.8	0.239	0.268	0.0480
102	100.55	78.8	0.239	0.268	0.0480
103	105.10	78.1	0.236	0.269	0.0474
104	101.60	78.8	0.238	0.268	0.0479
105	99.45	79.0	0.240	0.268	0.0481

Table 2 (concl.)

Run No.	Average bulk temperature of Freon-12 °F	Density ρ lb/ft^3	Viscosity μ centipoise	Specific heat C_{p_f} B/lb °F	Thermal conductivity k_b B/hr-ft-°F
106	101.95	78.8	0.238	0.268	0.0478
107	98.95	79.1	0.240	0.268	0.0482
108	94.35	79.4	0.245	0.265	0.0487
109	94.85	79.4	0.245	0.265	0.0487
110	94.95	79.4	0.246	0.265	0.0487
111	99.65	79.0	0.240	0.268	0.0481
112	99.80	78.8	0.240	0.268	0.0481
113	99.20	79.1	0.240	0.268	0.0481
114	96.00	79.4	0.241	0.266	0.0485
115	96.75	79.4	0.240	0.266	0.0486
116	96.70	79.4	0.242	0.265	0.0485
117	98.85	79.1	0.241	0.267	0.0482
118	99.30	79.1	0.240	0.267	0.0481
119	102.80	78.4	0.239	0.269	0.0477
120	103.90	78.1	0.239	0.269	0.0475
121	105.30	78.1	0.238	0.270	0.0473
122	105.95	78.1	0.238	0.270	0.0471
123	103.25	78.3	0.239	0.269	0.0476
124	106.70	77.9	0.237	0.270	0.0472
125	104.90	78.1	0.238	0.269	0.0474
126	101.50	78.8	0.240	0.268	0.0479
127	98.10	79.4	0.241	0.267	0.0483
128	101.10	78.8	0.240	0.268	0.0479
129	104.50	78.1	0.238	0.269	0.0475
130	100.00	78.8	0.239	0.268	0.0480
131	100.85	78.8	0.239	0.268	0.0479
132	103.25	78.4	0.237	0.269	0.0476
133	98.10	79.4	0.240	0.267	0.0482
134	99.55	79.1	0.240	0.268	0.0481
135	97.25	79.4	0.240	0.267	0.0484
136	92.90	79.7	0.245	0.265	0.0489
137	98.75	79.1	0.240	0.267	0.0482
138	94.05	79.4	0.245	0.265	0.0487
139	100.35	78.8	0.238	0.268	0.0479
140	92.90	79.7	0.245	0.265	0.0489
141	99.05	79.1	0.240	0.268	0.0481
142	96.20	79.4	0.242	0.267	0.0485

APPENDIX E

Table 3. Calculated data of condensation of Freon-12 inside a single horizontal tube.

Run No.	Vapor velocity V ft/sec	Flow rate of condensate, W lb/hr	Mass velocity G, lb/hr-ft²	Rate of heat transfer, Q B/hr	Temperature difference $(t_b - t_s)$ ΔT_c °F.	Film coefficient of heat transfer, h_f B/hr-ft²-°F	Heat flux Q/A_1 B/hr-ft²	$\frac{DG}{\mu_b}$ (Re)	$\frac{h_f D}{k_b}$ (Nu)
1	13.0	182.5	134000	1605	13.04	470	6140	4050	378
2	10.7	150.0	110000	2050	14.87	526	7830	7440	421
3	16.0	224.5	164800	1965	18.04	415	7500	11350	351
4	20.5	286.5	210200	2195	20.44	410	8380	14990	352
5	19.1	267.0	196000	2345	21.11	424	8960	13950	364
6	10.6	148.7	109000	3035	24.26	476	11580	7460	401
7	10.5	147.5	108200	2360	24.29	371	9010	7450	314
8	10.4	146.5	107500	2390	21.38	427	9120	7550	365
9	10.5	146.5	107500	2245	22.64	379	8580	7650	326
10	10.4	146.5	107500	2300	26.68	329	8780	7680	283
11	10.4	146.5	107500	2360	23.80	379	9010	7550	324
12	10.5	146.5	107500	2358	23.61	380	9010	7550	325
13	12.2	170.5	125100	2750	28.39	370	10500	8970	321
14	12.2	171.0	125500	2585	28.74	344	9870	9000	297
15	12.4	174.3	128000	2710	28.53	363	10350	9170	314
16	12.4	174.5	128100	2540	28.53	339	9700	9180	293
17	12.4	174.5	128100	2525	28.65	338	9640	9180	292
18	12.5	175.0	128400	2525	28.54	349	9640	9180	300
19	12.5	175.0	128400	2570	27.60	337	9810	9200	291
20	12.5	175.0	128400	2730	27.10	360	10410	9200	311
21	13.7	192.0	140900	3150	31.67	380	12020	10220	332
22	11.85	166.0	121900	2860	24.11	454	10920	8550	387
23	11.88	166.2	122000	2845	25.45	427	10850	8560	363
24	13.51	184.5	135300	3485	30.37	438	13300	9670	377
25	13.51	184.5	135300	3480	28.61	464	13290	9640	398
26	13.51	184.5	135300	3260	26.98	461	12450	9500	394
27	13.59	187.5	137500	3460	27.48	467	12820	9800	401
28	13.4	187.5	137500	3155	28.85	417	12040	9880	360
29	13.35	187.0	137200	3080	28.54	413	11760	9850	356
30	13.5	189.5	139000	2980	30.05	374	11390	10000	324
31	20.5	287.0	210500	3760	29.75	382	14350	15420	426
32	20.2	283.0	207500	3490	29.08	458	13310	15100	400
33	20.1	282.0	207000	3865	30.55	483	14750	15100	424
34	19.7	276.0	202500	3720	28.74	494	14210	14790	434
35	12.5	175.0	128700	2570	29.10	337	9820	9210	291

Table 3 (cont.)

Run No.	Vapor velocity V ft/sec	Flow rate of condensate, W lb/hr	Mass velocity G, lb/hr-ft^2	Rate of heat transfer, Q B/hr	Temperature difference $(t_b - t_s)$ ΔT_c °F.	Film coefficient of heat transfer, h_f B/hr-ft^2-°F	Heat flux Q/A_1 B/hr-ft^2	$\frac{DG}{\mu_b}$ (Re)	$\frac{h_f D}{k_b}$ (Nu)
36	13.4	188.0	138000	3155	28.68	419	12030	9900	361
37	13.4	188.0	138000	3080	30.06	392	11780	9900	338
38	13.3	186.5	136900	3188	30.76	396	12180	9850	344
39	13.5	189.5	139000	3140	29.72	404	11990	10000	351
40	20.6	288.5	211800	3690	30.44	462	14090	15450	407
41	20.6	288.5	211800	3580	30.07	455	13680	15450	399
42	20.2	283.0	207900	3500	30.05	444	13370	15200	386
43	18.63	261.0	191500	3780	25.31	570	14420	13450	489
44	11.00	154.0	113000	2950	19.31	584	11270	7890	495
45	19.15	269.0	197200	4470	18.91	902	17070	13820	768
46	21.2	297.0	218000	5300	27.20	743	20200	15630	646
47	17.4	244.0	179000	3620	21.66	638	13810	12500	542
48	10.18	142.5	104700	2820	19.96	540	10780	7200	454
49	16.45	231.0	169500	3425	23.12	565	13080	11810	482
50	10.12	149.0	109400	2900	19.94	555	11080	7500	462
51	17.55	246.0	180700	3755	20.42	701	14310	12500	591
52	18.4	258.0	189400	4760	19.06	954	18160	13100	804
53	20.8	292.0	214500	5040	25.42	755	19200	15250	653
54	14.75	207.0	152000	3250	19.17	648	12410	10420	542
55	17.10	240.0	176000	4090	18.20	859	15610	12180	724
56	20.45	287.0	210000	5020	20.97	915	19170	14800	784
57	13.39	188.0	137900	3325	18.72	678	12690	9470	566
58	17.55	246.0	180500	3800	20.37	713	14510	12490	600
59	18.3	257.0	188500	4730	19.37	933	18020	13150	792
60	16.6	233.0	171000	3570	19.41	690	13400	11820	579
61	17.25	246.0	180400	2410	17.14	536	9200	12440	451
62	20.15	283.0	207800	2245	21.16	406	8580	14600	344
63	21.35	299.0	219500	3860	23.26	634	14740	15750	544
64	17.55	246.0	180500	2355	20.66	435	8990	12440	366
65	21.05	295.0	216500	3320	21.18	598	12670	15050	506
66	21.8	306.0	224500	3500	24.56	544	13350	16110	466
67	11.55	162.0	119000	2285	20.15	433	8720	8100	362
68	20.00	280.0	205700	3140	21.65	554	11990	14580	472
69	11.5	161.0	117200	2550	20.79	468	9740	8140	395
70	10.6	149.0	109200	2630	19.64	511	10040	7540	430

Table 3 (cont.)

Run No.	Vapor velocity V ft/sec	Flow rate of condensate, W lb/hr	Mass velocity G, lb/hr-ft^2	Rate of heat transfer, Q B/hr	Temperature difference $(t_b - t_s)$ ΔT_c °F.	Film coefficient of heat transfer, h_f B/hr-ft^2-°F	Heat flux Q/A_1 B/hr-ft^2	$\frac{DG}{\mu_b}$ (Re)	$\frac{h_f D}{k_b}$ (Nu)
71	20.45	286.5	210000	3980	21.26	715	15200	15100	614
72	21.2	297.0	217900	4280	24.16	677	16350	15700	589
73	10.54	147.5	108200	2420	20.39	454	9240	7530	384
74	20.0	280.5	205800	3680	20.49	685	14040	14600	586
75	9.8	137.8	101000	2490	18.95	501	9500	6900	420
76	16.92	237.5	174200	3120	21.69	549	11910	12100	465
77	18.65	261.0	191800	3810	22.18	656	14530	13750	564
78	19.60	275.0	202000	3370	21.78	591	12850	14370	504
79	9.7	137.5	101000	2380	18.98	479	9090	6840	400
80	17.9	250.5	184000	2140	16.09	517	12700	12700	436
81	18.8	263.5	193500	2480	16.59	570	13410	13410	482
82	19.55	274.0	201000	2850	19.66	554	14420	14420	476
83	12.47	175.0	128500	1775	15.40	440	8900	8900	370
84	16.42	230.0	168800	2145	17.68	458	11810	11810	391
85	19.10	267.5	196400	2825	19.59	550	13800	13800	471
86	21.10	296.0	217000	3420	25.84	505	15800	15800	443
87	11.32	159.0	116400	2190	16.07	521	8080	8080	447
88	17.35	243.0	178500	2120	18.97	427	12400	12420	364
89	18.75	256.0	188000	2530	17.35	556	13170	13170	475
90	21.45	300.0	220100	3240	20.62	600	15800	15800	495
91	10.19	142.5	104800	1665	17.03	373	7200	7200	313
92	16.50	231.0	169500	1715	19.00	395	11810	11810	292
93	18.65	261.0	191500	2160	19.22	429	13580	13580	366
94	12.95	181.5	133200	1768	18.75	360	9180	9180	303
95	18.35	257.0	188900	1935	22.34	331	13130	13130	281
96	20.00	280.0	205800	2900	24.79	447	14750	14750	386
97	18.80	263.0	193000	1925	23.37	310	13580	13580	264
98	19.7	276.0	202500	2240	20.88	410	14100	14100	349
99	20.65	290.0	212500	3310	29.94	422	15480	15480	370
100	19.70	276.0	202500	2395	21.83	418	14100	14100	355
101	19.38	272.0	199500	3300	25.42	496	12600	14390	431
102	19.38	272.0	199500	4700	24.82	723	17930	14390	627
103	19.25	269.5	197800	4530	27.12	638	17300	14400	560
104	18.92	265.5	194800	3135	25.57	469	11980	14090	408
105	18.95	266.5	195500	3810	24.73	588	14540	14010	508

Table 3 (concl.)

Run No.	Vapor velocity V ft/sec	Flow rate of condensate, W lb/hr	Mass velocity G, lb/hr-ft²	Rate of heat transfer, Q B/hr	Temperature difference $(t_b - t_s)$ ΔT_c ° F.	Film coefficient of heat transfer, h_f B/hr-ft²-°F	Heat flux Q/A_1 B/hr-ft²	$\frac{DG}{\mu_b}$ (Re)	$\frac{h_f D}{k_b}$ (Nu)
106	19.40	272.0	199500	2900	20.65	536	11090	14420	468
107	19.00	267.0	196000	2625	23.28	430	10010	14030	372
108	19.50	274.0	201000	3240	20.82	595	12380	14120	509
109	19.50	274.0	201000	3510	20.49	654	13400	14120	559
110	19.50	274.0	201000	3235	20.24	610	12340	14080	521
111	18.10	253.5	186000	2168	24.61	337	8300	13320	291
112	17.58	246.5	181000	2210	23.98	352	8440	12980	304
113	18.10	254.0	186500	2230	23.41	364	8520	13350	315
114	11.80	165.8	121700	1990	22.06	345	7600	8690	296
115	15.90	223.0	163700	2105	21.93	367	8040	11720	314
116	15.90	222.5	163400	2105	21.95	367	8040	11600	315
117	17.69	247.3	181800	2955	21.86	516	11290	12980	446
118	18.10	254.0	186500	2470	22.93	411	9430	13350	355
119	18.40	257.5	189000	2530	23.28	415	9670	13600	362
120	18.32	257.0	188800	2625	23.42	432	10010	13590	379
121	18.32	257.0	188800	2520	27.66	348	9620	13620	307
122	18.32	257.0	188800	2500	23.66	404	9540	13620	357
123	18.40	257.5	189000	2455	23.29	402	9370	13600	351
124	18.70	262.0	192500	2700	23.48	424	10310	13990	374
125	18.65	263.0	193000	2815	24.35	441	10760	13950	388
126	18.45	258.0	190300	2740	23.95	437	10470	13610	380
127	18.15	255.0	187000	2300	22.96	383	8780	13390	330
128	18.48	259.0	190000	2750	24.61	426	10500	13600	371
129	18.30	257.0	188800	2365	25.31	357	9030	13620	313
130	18.48	259.0	190000	2700	24.52	420	10300	13700	364
131	18.05	253.0	185800	2490	24.65	385	9500	13390	335
132	18.40	258.0	189500	2700	25.81	399	10300	13750	349
133	15.00	210.0	154200	1980	24.85	304	7560	11050	263
134	17.60	247.0	181000	2045	24.08	324	7800	13000	281
135	17.28	243.0	178000	2225	20.06	424	8500	12790	365
136	10.50	147.0	108000	1695	21.95	295	6460	7590	251
137	18.10	254.0	186000	2225	24.30	350	8500	13370	302
138	13.62	191.0	140300	2335	22.83	390	8910	9850	333
139	19.35	272.0	199500	2450	25.51	367	9350	14420	319
140	10.25	144.0	105800	2110	22.05	365	8050	7430	311
141	18.10	254.0	186200	1980	24.48	309	7550	14400	268
142	15.90	223.0	163600	1820	23.86	291	6950	11650	250

APPENDIX F

SAMPLE CALCULATION

<u>Run</u> <u>No</u>. <u>32</u>

Rate of flow of Freon-12 = 0.45 gpm

$$\text{Average bulk temperature of Freon-12} = \frac{92.3 + 113.9}{2}$$

$$= \frac{206.2}{2}$$

$$= 103.1° \text{ F}$$

$$\rho = 78.4 \ \frac{\text{lb}}{\text{cu ft}}$$ (Air Conditioning-Refrigerating Data Book)

Area of cross section of the inner condenser tube

$$= A = \frac{\pi}{A} \left(\frac{0.5}{12}\right)^2 = \frac{0.1962}{144} \text{ foot}^2$$

Freon-12 vapor velocity = V

$$= 0.45 \ \frac{\text{gal}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}} \times 0.1337 \ \frac{\text{ft}^3}{\text{gal}} \times 78.4 \ \frac{\text{lb}}{\text{ft}^3}$$

$$\times \ 0.35 \ \frac{\text{ft}^3}{\text{lb}} \times \frac{144}{0.1962 \text{ ft}^2} = 20.2 \text{ ft/sec}$$

Weight rate of Freon-12 = W

$$= 0.45 \ \frac{\text{gal}}{\text{min}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times 0.1337 \ \frac{\text{ft}^3}{\text{gal}} \times 78.4 \ \frac{\text{lb}}{\text{ft}^3} = 283 \text{ lb/hr}$$

$$\text{Mass velocity of flow of Freon-12} = G = \frac{W}{A}$$

$$= 283 \ \frac{\text{lb}}{\text{hr}} \times \frac{144}{0.1962 \text{ ft}^2} = 207{,}500 \ \frac{\text{lb}}{\text{hr-ft}^2}$$

Heat transferred to the cooling water in the test section:

Weight rate of flow of cooling water = M = 585 lb/hr

$$Q = M \cdot C_{pw} \cdot \Delta_t$$

$$= 585 \times 1 \times 5.96$$

$$= 3490 \text{ B/hr}$$

Average temperature of outside surface of inner condenser tube = 72.03° F

Heat transferred by conduction through the metal:

$$Q = k_m A_m \frac{\Delta t_b}{\Delta_x}$$

Area of inside surface of inner condenser tube

$$= A_1 = \frac{\pi (0.5)^2}{12} = 0.262 \text{ ft}^2$$

Area of outside surface of inner condenser tube

$$= A_2 = \frac{\pi (0.753)^2}{12} = 0.395 \text{ ft}^2$$

Logarithmic mean area $= A_m = \dfrac{A_2 - A_1}{\ln \dfrac{A_2}{A_1}}$

$$= \frac{0.395 - 0.262}{\ln \dfrac{0.395}{0.262}} = 0.323 \text{ ft}^2$$

$$k_m = 57.0 \frac{B}{\text{hr-ft °F}}$$ (Heat transmission, McAdams, P. 447)

$$\Delta t_b = \frac{Q \cdot \Delta_x}{k_m A_m} = \frac{3490 \times 0.126}{57.0 \times 0.323 \times 12} = 1.99° \text{ F}$$

Average temperature of inside surface of inner condenser tube = 72.03 + 1.99 = 74.02° F

Heat transferred through Freon-12 vapor film:

$$Q = h_f \times A_1 \times \Delta T_c$$

Temperature difference between inside surface of inner condenser tube and Freon-12 vapor

$$= \Delta T_c = 103.1 - 74.02 = 29.08° \text{ F}$$

Film coefficient of heat transfer $= h_f = \dfrac{Q}{A_1 \cdot \Delta T_c}$

$$= \frac{3490}{0.262 \times 29.08} = 458 \; \frac{B}{hr\text{-}ft^2 \; °F}$$

Heat flux $= \dfrac{Q}{A_1} = \dfrac{3490}{0.262} = 13310 \; \dfrac{B}{hr\text{-}ft^2}$

APPENDIX G

METHOD OF LEAST SQUARE

(3), P. 192-215

The method for obtaining the straight line which fits a linear trend best is called the method of least squares because it makes the sum of squares of the vertical deviations of the points from the regression line a minimum.

The term regression line is used to describe the line chosen to represent the relationship between two variables when this decision is based on sample points, as in the scatter diagram.

For a given value X_i of the measurement X, let the corresponding value of Y be called Y_i if it was observed with X_i when the sample was taken. It will be designated as $\hat{Y}_i$ if it is calculated from the equation of the regression (trend) line. Also, let the general linear equation relating Y_i and X_i be written in the form

$$\hat{Y}_i = a + b(X_i - \bar{x})$$

where a and b are the two constants which must be determined in order to have a specific regression line for a particular scatter diagram.

Let $\bar{x}$ and $\bar{y}$ be the arithmetic mean of X_i and Y_i, respectively, such that

$$\bar{x} = \frac{\sum_{i=1}^{N} (X_i)}{N} \quad \text{and} \quad \bar{y} = \frac{\sum_{i=1}^{N} (Y_i)}{N}$$

where N is the number of measurements.

A measure of the dispersion or variation of the measurements, X_i, about their arithmetic mean, $\bar{x}$, logically would be based upon the amounts by which the X_i are greater than or less than that mean.

$\therefore \; x_i = X_i - \bar{x}$

Similarly, $y_i = Y_i - \bar{y}$

where x_i and y_i are called the deviations from the mean.

The estimated standard deviation of Y_i about the regression line is given by

$$S_{y \cdot x} = \sqrt{\frac{\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2}{N - 2}}$$

where the divisor, N - 2, is called the number of degrees of freedom for the estimated standard deviation about the linear trend line.

The best fitting straight line is chosen as that one for which the $\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2$ is a minimum. This makes the standard deviation about the trend line as small as possible.

$$\therefore \sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{N} (Y_i - a - bx_i)^2 = U$$

U could be minimized by the choice of "a" and "b".

Differentiating U partially with respect to a,

$$\frac{\partial U}{\partial a} = -2 \sum_{i=1}^{N} (Y_i - a - bx_i)$$

To be a maximum or minimum,

$$\frac{\partial U}{\partial a} = 0 = -2 \sum_{i=1}^{N} (Y_i - a - bx_i)$$

$$\therefore \sum_{i=1}^{N} (Y_i) - Na - b \sum_{i=1}^{N} x_i = 0$$

$$\text{Now } \sum_{i=1}^{N} x_i = \sum_{i=1}^{N} (X_i - \bar{x}) = \sum_{i=1}^{N} (X_i) - N \cdot \bar{x}$$

$$= N \cdot \bar{x} - N \cdot \bar{x} = 0$$

$$\therefore \sum_{i=1}^{N} (Y_i) = Na$$

$$\therefore a = \frac{\sum_{i=1}^{N} (Y_i)}{N} = \bar{y}$$

Also, by differentiating U partially with respect to b,

$$\frac{\partial U}{\partial b} = -2 \sum_{i=1}^{N} \left\{ x_i (Y_i - a - b\, x_i) \right\} = 0$$

$$\therefore \sum_{i=1}^{N} \left\{ x_i (Y_i - \bar{y} - b\, x_i) \right\} = 0$$

$$\therefore \sum_{i=1}^{N} \left\{ x_i (y_i - b\, x_i) \right\} = 0$$

$$\therefore \sum_{i=1}^{N} (x_i y_i) - b \sum_{i=1}^{N} (x_i^2) = 0$$

$$\therefore \quad b = \frac{\sum_{i=1}^{N}(x_i y_i)}{\sum_{i=1}^{N}(x_i^2)}, \quad \text{for brevity} \quad b = \frac{\sum (xy)}{\sum (x^2)}$$

By differentiating again partially with respect to a and b, it can be shown that these values of a and b give the minimum value of U.

$$\text{Again} \sum_{i=1}^{N} (x_i^2) = \sum_{i=1}^{N} (X_i - \overline{x})^2$$

$$= \sum_{i=1}^{N} (X_i^2 - 2\overline{x}\, X_i - \overline{x}^2)$$

$$= \sum_{i=1}^{N}(X_i^2) - 2\overline{x} \sum_{i=1}^{N}(X_i) + N \cdot \overline{x}^2$$

$$= \sum_{i=1}^{N}(X_i^2) - 2N \cdot \overline{x}^2 + N\, \overline{x}^2$$

$$= \sum_{i=1}^{N}(X_i^2) - N \cdot \overline{x}^2$$

$$\therefore \sum (x^2) = \sum (X_i^2) - N \cdot \overline{x}^2 = \sum (X_i^2) - \frac{\left[\sum (X_i)\right]^2}{N}$$

$$\text{Also} \sum_{i=1}^{N} (x_i y_i) = \sum_{i=1}^{N}(X_i - \overline{x})(Y_i - \overline{y})$$

$$= \sum_{i=1}^{N}(X_i Y_i - \overline{x} Y_i - \overline{y} X_i + \overline{x}\, \overline{y})$$

$$= \sum_{i=1}^{N}(X_i Y_i) - \overline{x} \sum_{i=1}^{N}(Y_i) - \overline{y} \sum_{i=1}^{N}(X_i) + N\, \overline{x}\, \overline{y}$$

$$= \sum_{i=1}^{N}(X_i Y_i) - N\, \overline{x}\, \overline{y} - N\, \overline{x}\, \overline{y} + N\, \overline{x}\, \overline{y}$$

$$= \sum_{i=1}^{N} (X_i Y_i) - N \bar{x} \bar{y}$$

$$= \sum_{i=1}^{N} (X_i Y_i) - \frac{\sum_{i=1}^{N} (X_i) \cdot \sum_{i=1}^{N} (Y_i)}{N}$$

$$\therefore b = \frac{\sum (xy)}{\sum (x^2)} = \frac{\sum (XY) - \frac{\sum (X) \cdot \sum (Y)}{N}}{\sum (X)^2 - \frac{\left[\sum (X)\right]^2}{N}}$$

Estimated standard deviation $= Sy \cdot x = \sqrt{\frac{\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2}{N - 2}}$

Again $\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{N} (Y_i - \bar{y} - b\, x_i)^2$

$$= \sum_{i=1}^{N} (y_i - b\, x_i)^2$$

$$= \sum_{i=1}^{N} (y_i^2 - 2b\, x_i y_i + b^2 x_i^2)$$

$$= \sum_{i=1}^{N} (y_i^2) - 2b \sum_{i=1}^{N} (x_i y_i) + b^2 \sum_{i=1}^{N} (x_i^2)$$

$$= \sum_{i=1}^{N} (y_i^2) - 2 \frac{\sum_{i=1}^{N} (x_i y_i)}{\sum_{i=1}^{N} (x_i^2)} \cdot \sum_{i=1}^{N} (x_i y_i) + \frac{\left[\sum_{i=1}^{N} (x_i y_i)\right]^2}{\left[\sum_{i=1}^{N} (x_i^2)\right]^2} \cdot \sum_{i=1}^{N} (x_i^2)$$

$$= \sum_{i=1}^{N}(y_i^2) - 2\,\frac{\left[\sum_{i=1}^{N}(x_i y_i)\right]^2}{\sum_{i=1}^{N}(x_i^2)} + \frac{\left[\sum_{i=1}^{N}(x_i y_i)\right]^2}{\sum_{i=1}^{N}(x_i^2)}$$

$$= \sum_{i=1}^{N}(y_i^2) - \frac{\left[\sum_{i=1}^{N}(x_i y_i)\right]^2}{\sum_{i=1}^{N}(x_i^2)}$$

Again $\sum_{i=1}^{N}(y_i^2) = \sum_{i=1}^{N}(Y_i - \bar{y})^2$

$$= \sum_{i=1}^{N}(Y_i^2 - 2\,\bar{y}\,Y_i + \bar{y}^2)$$

$$= \sum_{i=1}^{N}(Y_i^2) - 2\,\bar{y}\sum_{i=1}^{N}(Y_i) + N \cdot \bar{y}^2$$

$$= \sum_{i=1}^{N}(Y_i^2) - 2\,\frac{\sum_{i=1}^{N}(Y_i)}{N} \cdot \sum_{i=1}^{N}(Y_i) + N\,\frac{\left[\sum_{i=1}^{N}(Y_i)\right]^2}{N^2}$$

$$= \sum_{i=1}^{N}(Y_i^2) - \frac{\left[\sum_{i=1}^{N}(Y_i)\right]^2}{N}$$

$$\therefore S_{y \cdot x} = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{N - 2}}$$

$$= \sqrt{\frac{\sum(y^2) - \frac{\sum(xy)^2}{\sum(x^2)}}{N - 2}}$$

where $$\sum(y^2) = \sum(Y^2) - \frac{[\sum(Y)]^2}{N}$$

The standard deviation about the trend line, $S_{y.x}$, also is specifically useful in certain applications of linear trend analysis.

The regression coefficient, b, estimates the average change in the Y-measurement for each unit increase in the X-measurement. Its accuracy is measured by its standard deviation. The standard deviation of b is given by the formula

$$S_b = \frac{S_{y\,.\,x}}{\sqrt{\sum(x^2)}}$$

Another important application of linear trend analysis which makes use of $S_{y.x}$ is one in which Y is to be estimated for some unobserved value of X. The substitution of the value of X in the equation of the regression line will give the value of $\hat{Y}$. The standard deviation of $\hat{Y}$ is given by the following formula:

$$S\,\hat{Y} = S_{y.x}\sqrt{\frac{1}{N} + \frac{(X - \bar{\bar{x}})^2}{\sum x^2}}$$

where X is the value used to calculate $\hat{Y}$. This estimate of the standard deviation of $\hat{Y}$ is based on N - 2 degrees of freedom. This standard deviation applies when the X's have been chosen in advance and are not subject to sampling error.

APPENDIX H

Sample Calculation

<u>Position 2</u>

$$N = 18$$

$$\sum X = 73.1939$$

$$\bar{x} = \frac{\sum X}{N} = \frac{73.1939}{18} = 4.0663$$

$$\sum Y = 49.9904$$

$$\bar{y} = \frac{\sum Y}{N} = \frac{49.9904}{18} = 2.7772$$

$$\frac{\left[\sum X\right]^2}{N} = \frac{(73.1939)^2}{18} = 297.6304$$

$$\sum (X^2) = 297.8081$$

$$\sum (x^2) = \sum (X^2) - \frac{\left[\sum X\right]^2}{N}$$

$$= 297.8081 - 297.6304 = 0.1777$$

$$\sum (X \cdot Y) = 203.3775$$

$$\frac{(\sum X)(\sum Y)}{N} = \frac{73.1939 \times 49.9904}{18} = 203.2774$$

$$\sum (xy) = \sum (X \cdot Y) - \frac{(\sum X) \cdot (\sum Y)}{N}$$

$$= 203.3775 - 203.2774$$

$$= 0.1001$$

$$\therefore \quad a = \bar{y} = 2.7772$$

$$b = \frac{\sum(xy)}{\sum(x^2)} = \frac{0.1001}{0.1777} = 0.5633$$

$\therefore$ Equation of the regression line is

$$\hat{Y} = \bar{y} + b\,(X - \bar{x})$$

$$= 2.7772 + 0.5633\,(X - 4.0663)$$

$$= 2.7772 + 0.5633\,X - 2.2905$$

$$\therefore \hat{Y} = 0.4867 + 0.5633\,X$$

To find the standard deviation:

$$\sum(Y^2) = 138.9566$$

$$\frac{\left[\sum Y\right]^2}{N} = \frac{(49.9904)^2}{18} = 138.8356$$

$$\sum(y^2) = 138.9566 - 138.8356$$

$$= 0.1210$$

$$\sum(xy) = 0.1001$$

$$\therefore \left[\sum(xy)\right]^2 = (0.1001)^2 = 0.01002$$

$$\sum(x^2) = 0.1777$$

$$\therefore \frac{\left[\sum(xy)\right]^2}{\sum(x^2)} = \frac{0.01002}{0.1777} = 0.0564$$

$$\therefore \text{Standard deviation} = S_{y.x} = \sqrt{\frac{\sum(y^2) - \dfrac{\left[\sum(xy)\right]^2}{\sum(x^2)}}{N-2}}$$

$$= \sqrt{\frac{0.1210 - 0.0564}{16}}$$

$$= \sqrt{\frac{0.0646}{16}}$$

$$= \sqrt{0.004038}$$

$$= 0.06354$$

Standard deviation of b = $S_b = \dfrac{S_{y \cdot x}}{\sqrt{\sum (x^2)}}$

$$= \frac{0.06354}{\sqrt{0.1777}}$$

$$= \frac{0.06354}{0.4215}$$

$$= 0.1507$$

Standard deviation of $\hat{Y}$ = $S_{\hat{Y}} = S_{y.x}\sqrt{\frac{1}{N} + \frac{(X - \overline{x})^2}{\sum (x^2)}}$

$$= 0.06354\sqrt{\frac{1}{18} + \frac{(X - 4.0663)^2}{0.1777}}$$

Summary of the Results Obtained by
Method of Least Squares

Position 1

Equation of the regression line is

$$\hat{Y} = 0.2216\ X + 1.6593 \qquad \text{(11a)}$$

$$S_{y.x} = 0.04793$$

$$S_b = 0.06705$$

$$S_{\hat{Y}} = 0.04793\sqrt{\frac{1}{42} + \frac{(X - 4.0015)^2}{0.5109}}$$

Position 2

$$\hat{Y} = 0.5633\ X + 0.4867 \qquad \text{(11b)}$$

$$S_{y \cdot x} = 0.06354$$

$$S_b = 0.1507$$

$$S\,\hat{Y} = 0.06354\sqrt{\frac{1}{18} + \frac{(X - 4.0663)^2}{0.1777}}$$

Position 3

Equation of the regression line is

$$\hat{Y} = 0.3416\,X + 1.2730 \qquad (11c)$$

$$S_{y \cdot x} = 0.06301$$

$$S_b = 0.1067$$

$$S\,\hat{Y} = 0.06301\sqrt{\frac{1}{19} + \frac{(X - 4.0666)^2}{0.3489}}$$

Position 4

Equation of the regression line is

$$\hat{Y} = 0.2462\,X + 1.5720 \qquad (11d)$$

$$S_{y \cdot x} = 0.08222$$

$$S_b = 0.1955$$

$$S\,\hat{Y} = 0.08222\sqrt{\frac{1}{21} + \frac{(X - 4.0954)^2}{0.1844}}$$

Position 5

Equation of the regression line is

$$\hat{Y} = 0.6866\,X - 0.2657 \qquad (11e)$$

$$S_{y \cdot x} = 0.08601$$

$$S_b = 0.1943$$

$$S\,\hat{Y} = 0.08601\sqrt{\frac{1}{42} + \frac{(X - 4.1970)^2}{0.1959}}$$

FILM COEFFICIENT OF HEAT TRANSFER OF FREON-12 CONDENSING INSIDE A SINGLE HORIZONTAL TUBE

by

SURENDRAKUMAR PARBHUBHAI PATEL

B. S., University of Nebraska, 1954

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Film coefficients of heat transfer of Freon-12 condensing inside a single horizontal tube were investigated for a range of variables attainable with the present equipment. Dimensional analysis of the factors involved led to the development of the following equation.

$$\frac{h_f D}{k_b} = C \left(\frac{DG}{\mu_b} \right)^n$$

The apparatus used in this investigation consisted of a boiler, superheater, horizontal condenser, vertical condenser, Brooks Rotameter, potentiometer, immersion heater, pressure gages, pressure control gage, etc.

A conventional double-pipe heat exchanger, consisting of a 1/2-inch inside diameter brass pipe jacketed by a 13/16-inch inside diameter brass pipe was used. The length of the condenser was established at 10 feet to minimize the end effects. The center 2-foot section was selected as the test section.

Water was used as the cooling medium. The temperatures of the Freon-12 vapor and the cooling water were measured at the inlet and at the outlet of the condenser. Temperatures of the pipe wall and also the temperature rise of cooling water were measured along the test section at five points, each six inches apart. An immersion heater with maximum capacity of five kilowatts was used as a source of energy input.

A total of 142 runs were made for five pipe-wall thermocouple positions of 0, 45, 90, 135, and 180 degrees. The film coefficient of heat transfer was obtained from the data by using the following equations:

$$Q = M\, C_{pw} \,\Delta t_w = k_m\, A_m \frac{\Delta t_b}{\Delta x} = h_f\, A_1\, \Delta T_c$$

Experiments covered a range of Reynolds' number, DG/μ_b of 6800 to 16,100, a range of film coefficient of heat transfer, h_f, from 295 to 950, B/hr-ft^2 °F, and a range of heat flux, Q/A_1, of 6000 to 20,200 B/hr-ft^2. The following dimensionless equation was obtained to fit the data.

$$\frac{h_f D}{k_b} = 10.17 \left(\frac{DG}{\mu_b}\right)^{0.4013}$$

The conclusions are:

1. The film coefficient of heat transfer decreases with the increase in temperature drop across the film.
2. An increase in mass velocity will increase the film coefficient of heat transfer.
3. Heat transfer rate increases with increasing mass velocity.
4. The correlation obtained can be used to predict the film coefficient of heat transfer for Freon-12 inside a horizontal tube.