MODIFICATION OF A FORCED CONVECTION HEAT TRANSFER LOOP FOR USE WITH BINARY MIXTURES

By

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HEAT TRANSFER LOOP FOR USE

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CHAPTER I

INTRODUCTION

Available literature indicates that the use of a binary mixture in a forced convection heat transfer loop has received relatively little attention in research. For this reason, the School of Mechanical Engineering at Oklahoma State University undertook a project to determine the heat transfer and pressure drop characteristics during local boiling of a binary mixture in a forced convection heat transfer loop. These characteristics could then be compared with those for water and thereby provide a correlation that would be valuable to anyone desiring to use this type of local boiling heat transfer. Typical applications for which local boiling heat transfer may be advantageous include nuclear-reactor fuel elements, electronic power-tube cooling coils, and rocket-engine cooling jackets. (1).

The heat transfer loop used for this project was previously used by Tanger (2) and Philips (3), who used water as the circulating fluid. A study of the heat transfer loop indicated that the physical components were adequate for use with water and a small percent of volatile additive as the circulating fluid. This study also revealed that the operational characteristics and experimental instrumentation could be improved if certain modifications were performed on the heat transfer loop. It was felt that these modifications would also improve the accuracy of the experimental data.

This thesis describes the modifications that were accomplished, the reason for the modifications, and the results of the modifications. The component parts modified or added were:

1. Manometer system
2. Test section
3. Pressure control system
4. Thermal guard for the test section
5. Main circulating pump

In addition to these modifications, this thesis includes a description of the method and results of the calibration of the thermocouples and orifice that will be used in the heat transfer loop.

CHAPTER II

MANOMETER SYSTEM

One of the major purposes of the research project was to determine the pressure drop of the mixture flowing in the test section. In order to obtain more accurate data every effort was made to insure that all sources of error were removed from the manometer system. This was accomplished by modifying the following components of the manometer system: (1) Bypass arrangement, (2) Manometer fluid, (3) Manometer piping, (4) Check valves.

Bypass Arrangement

While becoming familiar with the operation of the heat transfer loop, it become apparent that it would be very difficult to remove the trapped air from the manometers. This problem was eliminated by the installation of a bypass arrangement. A sketch of the arrangement is shown in Figure 1.

The bypass was constructed of 1/4-inch copper tubing and a control valve inserted between the high and low pressure sides of the manometer. The bypass arrangement operated in the following manner: With the system under a pressure of approximately 50 pounds per square inch gage (psig) the valve between the pressure tap and the manometer was closed and the bypass valve opened. The bleed valve

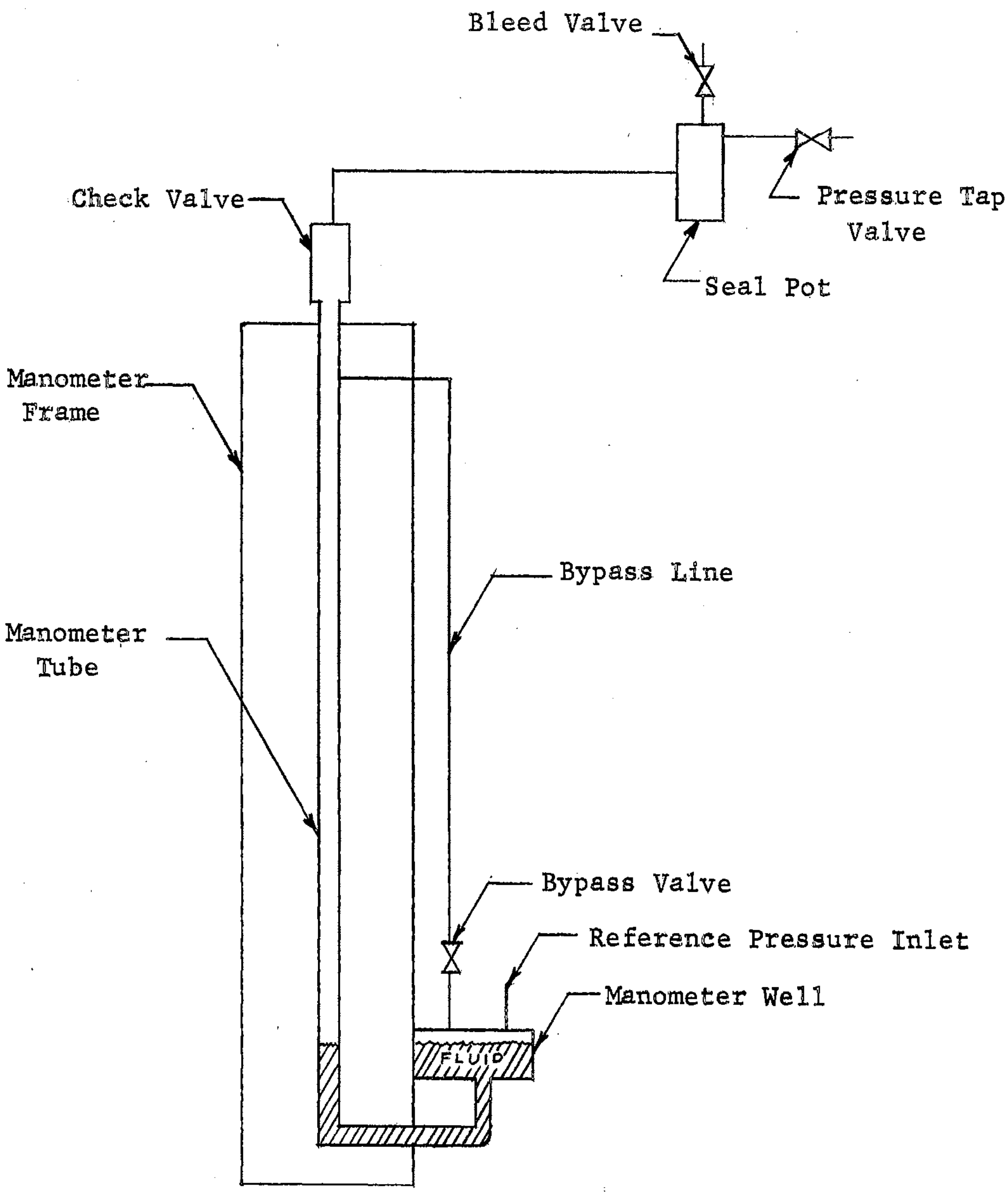


Figure 1. Sketch of the Manometer Bypass Arrangement

on top of the seal pot was then slowly opened. This exposed the manometer system to reference pressure on one side and atmospheric pressure on the other side. The difference in pressure caused the system fluid to enter the manometer at the reference pressure inlet. The system fluid then forced the manometer fluid up the manometer and at the same time it flowed through the bypass. When the manometer fluid reached the upper limit of the manometer, the bleed valve was closed, allowing the manometer fluid to return to the manometer well. This procedure was repeated several times and each time the system fluid was circulated through the bypass.

The main advantage of the bypass arrangement was that it provided an easy method to remove all the air from the manometers and made it possible to zero the manometer regardless of the system pressure.

Manometer Fluid

Philips (3) reported that the meniscus of the manometer fluid was poorly defined because of deposits inside the manometer glass. In order to improve this situation, a sample of the manometer fluid used by Philips (3) and Tanger (2) (Meriam Number 3 red fluid having a specific gravity of 2.95) was studied to determine its corrosive effect on various materials. This study revealed that the fluid had a damaging effect on all materials tested except stainless steel and glass. This characteristic of the fluid produced small particles that would adhere to glass and distort the meniscus. Since the manometer fluid comes in contact with materials other than stainless steel, a different type of fluid was chosen to be used in the binary mixture project. The fluid chosen was Meriam Number D-8525 blud fluid having a specific gravity of 1.75. This fluid was also tested with various materials and it was determined that it had little or no effect on the materials tested. Therefore, very little difficulty was encountered while reading the manometers because of a poorly defined meniscus.

Another very important advantage of the blue fluid over the red fluid is its smaller specific gravity. Since water was used above the fluid in the manometers, a reading of 1 inch of the red fluid is equivalent to a 2.6 reading of blue fluid. This meant that a minor change in pressure drop would be much easier to detect with the blue fluid. For example, a change of 0.02 inches of the red fluid would not be within the readability of the manometer scale which is 0.05 inches. The same change would be 0.052 inches of the blue fluid, which is within the readability of the manometer scale.

Manometer Piping

The leads from the pressure taps to the manometer system used by Tanger (2) and Philips (3) were nylon reinforced polyethylene tubing. While operating the loop to determine the range of variables to be used, two of the leads ruptured which caused a safety hazard to the operating personnel as well as the possibility of damage to other components of the loop. The rupture was caused by a slight decrease in pressure drop which in turn caused boiling system fluid at high pressure to enter the piping.

To eliminate the possibility of additional ruptures, the nylon reinforced polyethylene tubing was replaced by 1/4-inch copper tubing. The copper tubing was looped midway between the test section and the seal pots. The size of the loop was approximately a 6-inch diameter circle. This allowed a greater area for the dissipation of heat so that fluid in the seal pots and therefore the fluid going to the manometers would be near or at room temperature. The looping of the copper tubing also provided flexibility to prevent strain on the pressure taps.

The copper tubing presented another problem because it electrically connected the test section to the seal pots which were mounted on the angle iron frame of the loop. This connection allowed some of the power supplied to the test section to be conducted to the frame of the heat transfer loop. The connection was eliminated by mounting the seal pots on a wooden beam attached to the frame of the heat transfer loop.

Check Valves

During the development of the bypass arrangement it was felt that a check valve should be installed on the top of each manometer. This valve would decrease the possibility of the escape of the manometer fluid into the system fluid during the bleeding process or during a sudden change in pressure. Meriam float valves No. 201 were obtained and installed. Figure 2 is a sectional view of the check valve. The

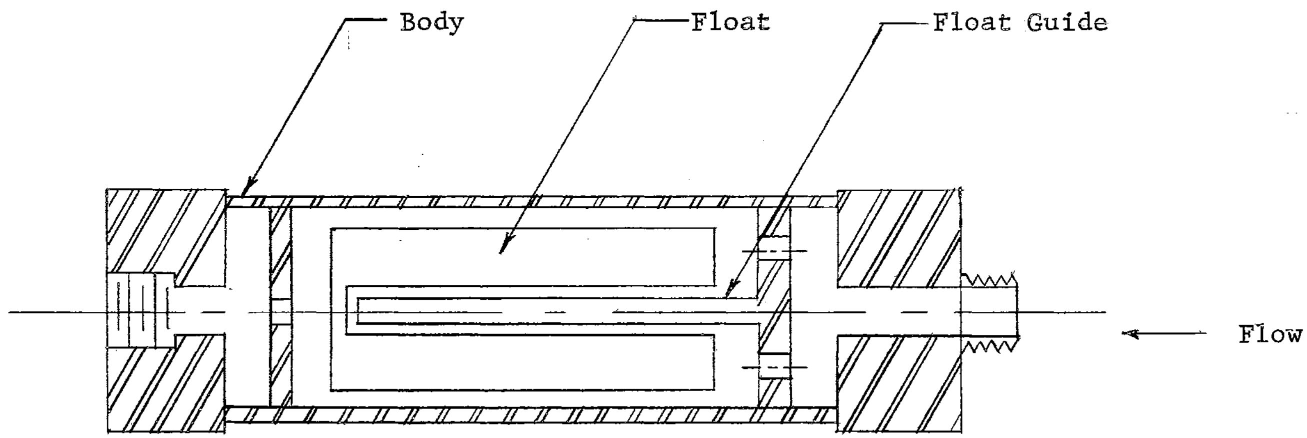


Figure 2. Sectional View of Manometer Check Valve

float of the valve is designed to permit the flow of water and check the flow of manometer fluid because it floats in manometer fluid and sinks in water. However, the check valve would not function properly because the float of the valve would not float in the manometer fluid. An attempt was made to relieve the situation by replacing the float with a cast polyethylene epoxy resin float which was fabricated in the Mechanical Engineering Laboratory. This did not prove successful because the neoprene seal glued to the slide would swell when exposed to the manometer fluid and thereby restrict the flow. However, after the removal of the neoprene seal the check valves performed adequately.

CHAPTER III

THE TEST SECTION

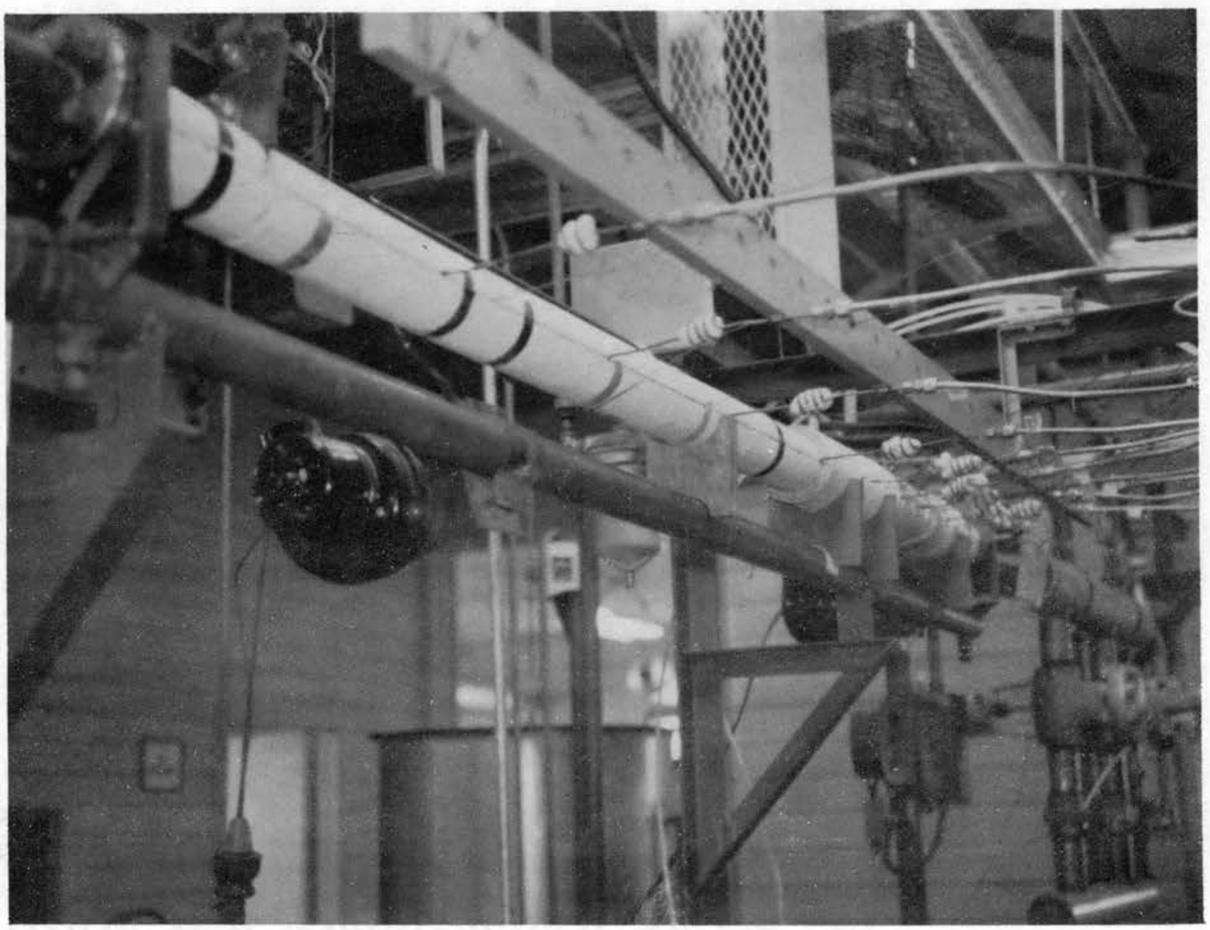
The test section used by Tanger (2) and Philips (3) was constructed of type 304 stainless steel tube with a 0.502-inch outside diameter and a 0.399-inch inside diameter. It was determined that this test section was acceptable for use with the binary mixture. However, some of the attachments to the test section were modified. Specifically, changes were made on the following components of the test section: (1) the pressure taps, (2) the thermocouples, and (3) the insulation surrounding the test section. An overall view of the test section is shown in Plate I.

The Pressure Taps

Tanger (2) reported that boiling took place in the last third of the test section at most flow rates. Considering this fact, additional pressure taps were attached to the latter part of the test section, making it possible to obtain more data in the boiling region. Since the heat transfer loop is equipped with only ten 60-inch manometers to be used with the pressure taps, it became necessary to seal some of the upstream pressure taps so that the additional pressure taps could be utilized. Also, the reference pressure tap was changed from a position of 3 inches downstream of the inlet flange, to a position of 9 inches

PLATE I

AN OVERALL VIEW OF TEST SECTION



downstream of the power inlet lug, thereby decreasing the possibility of any end effects that may have been present. The pressure taps were installed by the method described by Tanger (2). The exact location of the pressure taps is shown in Figure 3.

Thermocouples

Iron-constantan 30-gauge thermocouple wires were attached to the test section at the locations shown in Figure 3. Tanger (2) reported that the thermocouples were attached by spot welding. It was felt that this method of attachment could be improved if the thermocouples were electrically shielded from the test section. The electrical shield would eliminate the possibility of obtaining an erroneous temperature because of the thermocouple wire coming in contact with the test section in more than one place.

The electrical shielding was accomplished by wrapping a thin sheet of mica (Approximately 0.005 inches thick) around the test section prior to the attachment of the thermocouple. This method was successfully used by Rohsenow and Clark (4). The thermocouple was placed on the mica and held in place by an aluminum band approximately 1-inch wide. As the band was tightened, the thermocouple became rigidly placed and could be exactly located since the thermocouple junction created a bulge in the aluminum band. A sketch of an attached thermocouple is shown in Figure 4.

The thermocouples were connected to a Leeds and Northrup portable precision potentiometer which made it possible to determine with use of

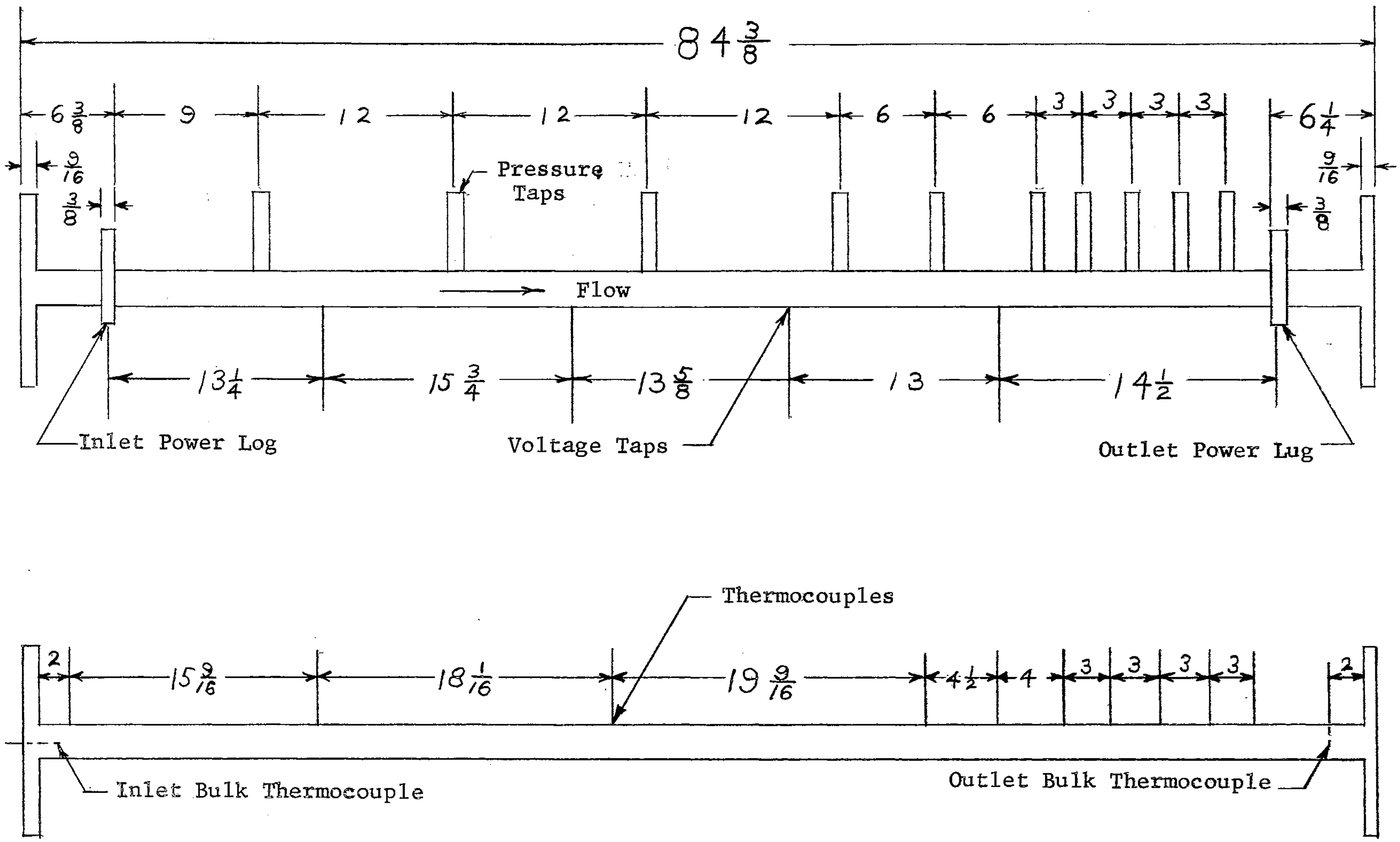


Figure 3. Modified Test Section and Attachments

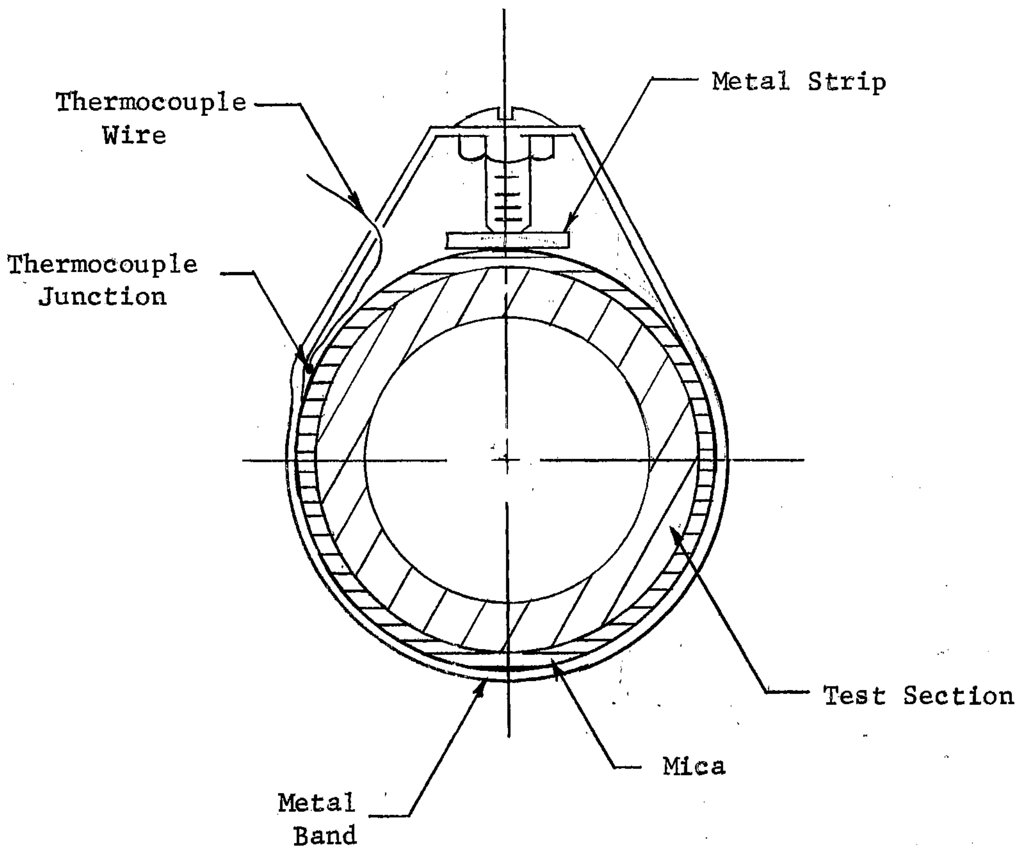


Figure 4. Sketch of Thermocouple Attachment

the thermocouple calibration data, (Chapter VII), the temperature within 1/3 of one degree Fahrenheit. This method of determining temperature is much more accurate than the method used by Tanger (2) and Philips (3) as their temperatures were reported accurate within 1.5 degrees Fahrenheit.

Insulation

After the relocation of the pressure taps and the attachment of the thermocouples, the test section was carefully wrapped with two layers of 1/16-inch thick asbestos. A solid insulation of 2 inches of 85% magnesia was then placed around the test section and held in place by metal clamps. The two insulating materials provided a total of 2 1/8 inches of insulation.

CHAPTER IV

PRESSURE CONTROL SYSTEM

Philips (3) and Levengood (5) reported that difficulty was encountered in maintaining equilibrium conditions during operation of the heat transfer loop. Since the pump speed can be held constant (and therefore the flow rate) and the average power variations are small, it appears that the system pressure was the major factor contributing to their difficulty in maintaining equilibrium. One source of their difficulty may have been the 3/4-inch stainless steel needle valve which was used to control pressure manually. The expansion of this valve with increasing temperature may have caused changes in pressure which hampered the achievement of equilibrium.

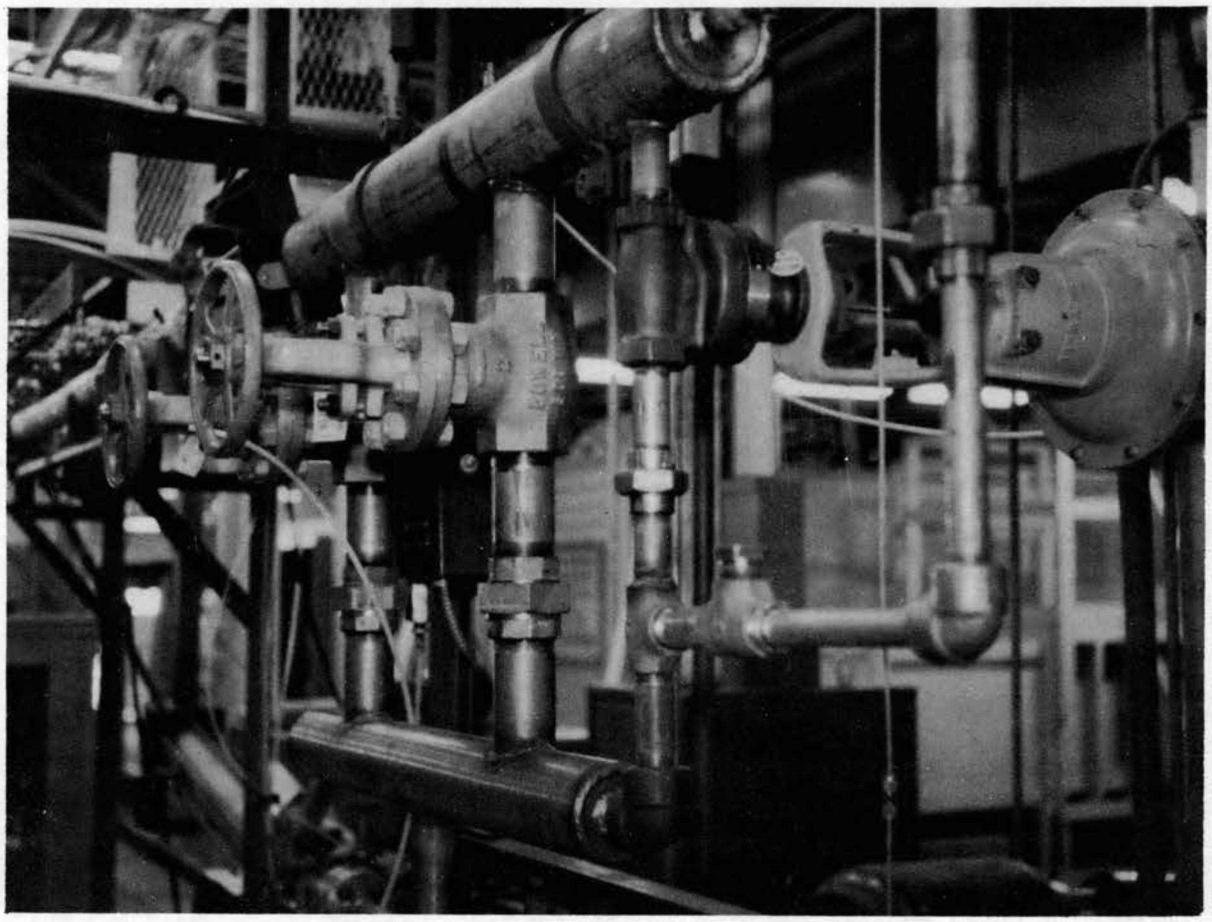
Considering this situation, the pressure control system was modified by replacing a 1-inch Globe valve in the exhaust manifold with a Number 800 Diaphragm motor valve manufactured by Minneapolis-Honeywell. A view of the installation is shown in Plate II. The diaphragm valve was controlled by a Tel-O-Set Two-Mode Adjustable Band Controller, manufactured by Brown Instrument Division of Minneapolis Honeywell. This controller was activated by a pneumatic transmitter.

Diaphragm Valve

The diaphragm valve was installed in the exhaust manifold as shown

PLATE II

VIEW OF THE EXHAUST MANIFOLD WITH
THE DIAPHRAGM VALVE



in Plate II, upstream of the 3/4-inch needle valve. The needle valve was not used. The diaphragm valve is activated by an input air pressure of 3 to 15 pounds per square inch from the Tel-O-Set controller.

Pneumatic Transmitter

The pneumatic transmitter is a device which receives the system pressure via nylon tubing from the reference pressure tap and then transmits a proportional pressure to the Tel-O-Set controller. This transmitter has an adjustable proportioning band of 0 to 100 percent and is operated with an input air pressure of 20 pounds per square inch. The transmitter output pressure is 3 to 15 pounds per square inch.

Tel-O-Set Controller

The Tel-O-Set controller is a pneumatic-balance device which develops an output pressure as a function of the difference between a set point pressure and a pressure representing the value of the process variable. (6). The controller develops and transmits a 3 to 15 pound per square inch controlled output pressure to the diaphragm valve. The controlled output pressure is dependent upon the relationship between the set point and the magnitude of the deviation of the variable from the set point. This is proportional control action. The reset component is proportional to the magnitude and the elapsed time of the deviation. The operation of the components will be discussed later in this chapter.

The adjustable band controller is sensitive to changes in the output pressure of the pneumatic transmitter of as little as 0.005 pounds per square inch. A 100% change in the output pressure of the pneumatic transmitter will result in a 63.2% controlled output response within 2.2 or 11.0 seconds, depending upon the proportional band setting and the control system characteristics.

The Tel-O-Set controller has a manual and automatic control switch. This switch permits operation of the control manually while changing the variables of the loop and then automatic control prior to reaching equilibrium and during each run.

Operation

The system pressure is directed to the pneumatic transmitter via nylon tubing from the reference pressure tap. The pneumatic transmitter then converts the system pressure to a proportional air pressure and then transmits this pressure to the Tel-O-Set controller. If this pressure is different than the desired pressure which is preset in the controller, the controller automatically transmits a signal via air pressure to the diaphragm valve which opens or closes the valve the appropriate amount to obtain the desired system pressure. A sketch of the pressure control system is shown in Figure 5.

Whenever the system pressure or flow rate is changed by an appreciable amount, the proportional band and reset rate of the Tel-O-Set controller must be changed. The changes are accomplished by the following steps. (6)

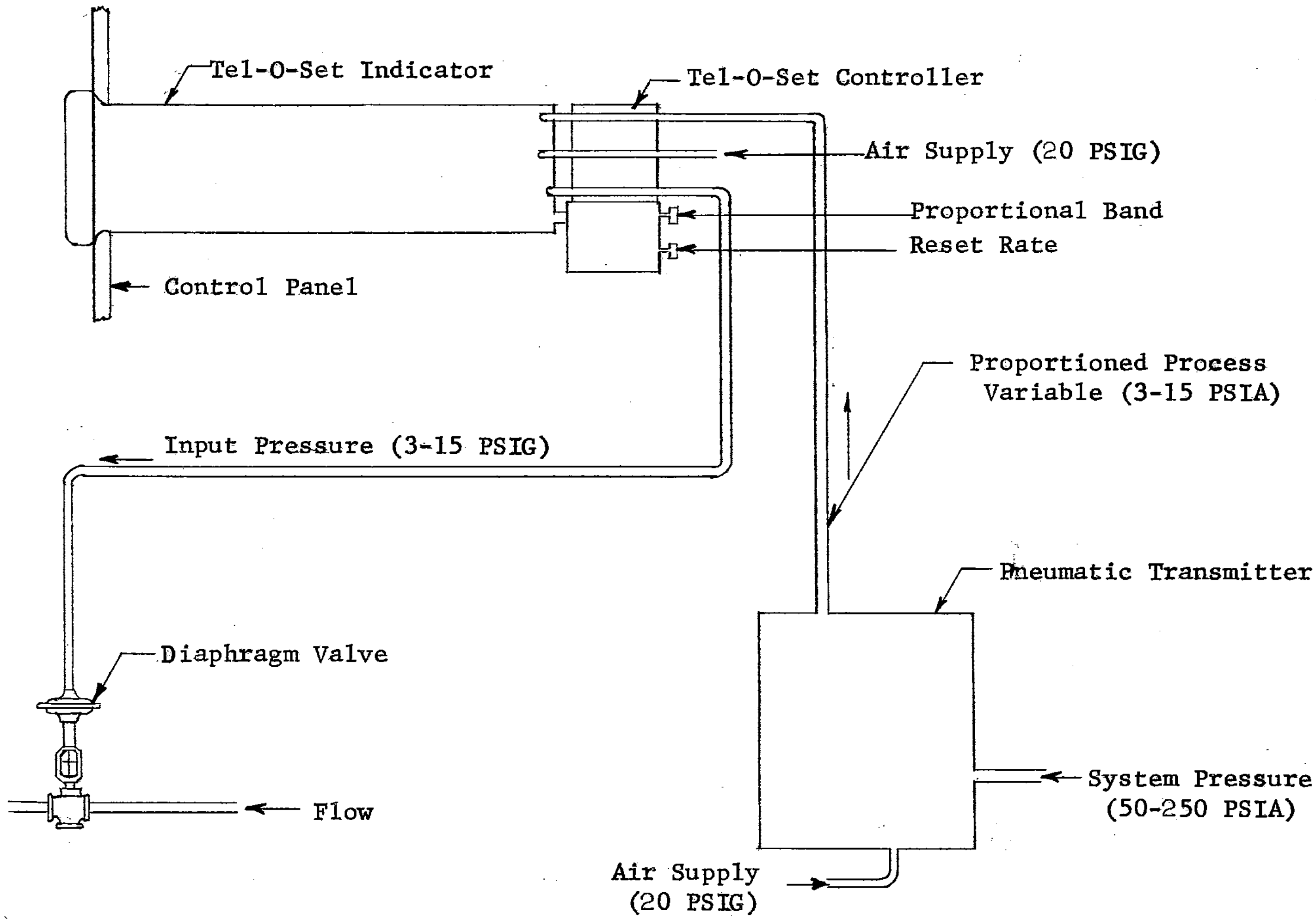


Figure 5. Sketch of Pressure Control System

1. With the reset rate control at zero, introduce a small upset into the system by opening and closing the system bypass valve.
2. Observe the amplitude pattern of the upset on the pressure gauge and adjust the proportional band on the controller until the amplitude is constant.
3. Measure the period of the pressure fluctuation.
4. Take the reading from the proportional band dial and multiply it by 2.2. This computed value is the approximate proportional band setting.
5. Divide 1.2 by the period of the process (in minutes) obtained in step 3. This provides the approximate reset rate in repeats per minute.
6. Make the computed control settings. The controller is now properly tuned, although slight tunings of the proportional band and reset rate may be necessary in order to maintain a specific pressure.

This modification with proper use of the Tel-O-Set controller made it possible to automatically maintain a given pressure within 0.5 pounds per square inch. The ease of operation of the heat transfer loop was also increased by this modification because equilibrium was attained more readily with constant system pressure.

CHAPTER V

THERMAL GUARD FOR THE TEST SECTION

The calculation of heat transfer is dependent upon the temperature of the test section in the boiling region. The temperature was determined by use of thermocouples attached to the test section as described in Chapter III. The accuracy of the temperature as measured by the thermocouple can be increased if the thermocouple is in an isothermal region. This insures that there is no thermal gradient along the thermocouple wire.

An isothermal region was provided for the boiling region of the test section by the fabrication and attachment of an electrically heated thermal guard. The guard, with insulation between the test section and the guard, provided an isothermal region by making the guard temperature equal to the test section wall temperature. This method proved to be very satisfactory in the work reported by Rohsenow and Clark (4).

Fabrication and Installation

The thermal guard was fabricated by placing a ceramic material around the insulated test section. This material was used rather than metal because it was not susceptible to inductive heating from the power passing through the test section. The ceramic material had an inside diameter of 3 inches, a thickness of 0.5 inches and a length of 26 1/2 inches. Since the boiling region is in the downstream third of the test section, the guard was installed over only that portion of the test section.

Four thermocouples were placed between the thermal guard and the insulated test section. One of these thermocouples was connected to a Brown Electronik recorder manufactured by Minneapolis-Honeywell. The remaining three thermocouples were connected to the Leeds and Northrup potentiometer. An additional thermocouple was attached to the test section in such a position as to be directly under a thermocouple between the guard and the insulation. Both of these thermocouples were attached to the Brown recorder.

The heating of the guard was accomplished by wrapping the ceramic material with Number 20 Nichrome wire. The power through the wire was controlled by a Variac and measured by a Simpson Model 390, Volt Amp Wattmeter.

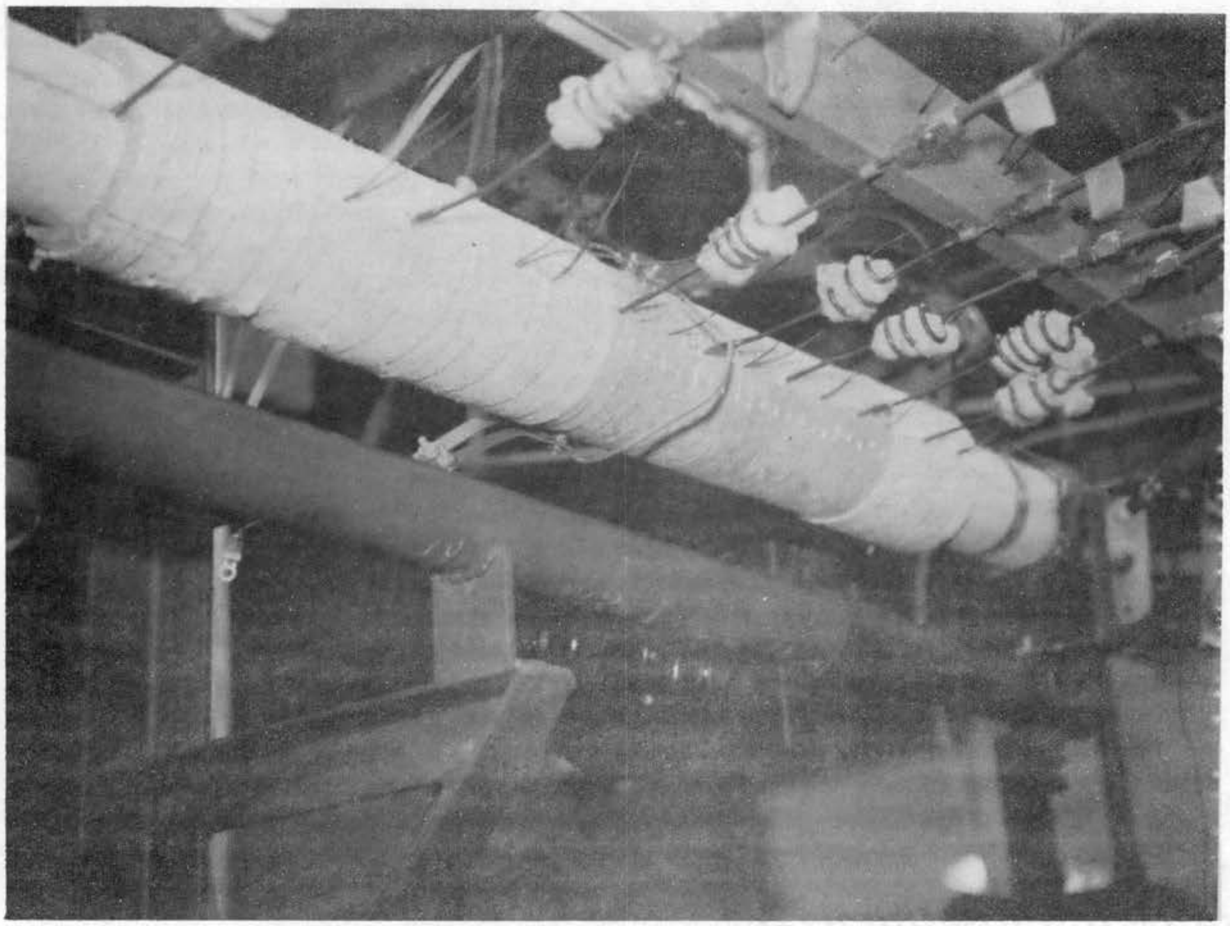
After the heating wires were checked for proper operation, the guard was placed around the insulated test section. The entire guard was then wrapped with two layers of 1/16-inch asbestos. Plate III is a view of the installed thermal guard partially wrapped with asbestos. Figure 6 is a sketch of the test section, insulation, and thermal guard.

Operation

The power to the thermal guard was turned on approximately

PLATE III

VIEW OF INSTALLED THERMAL GUARD



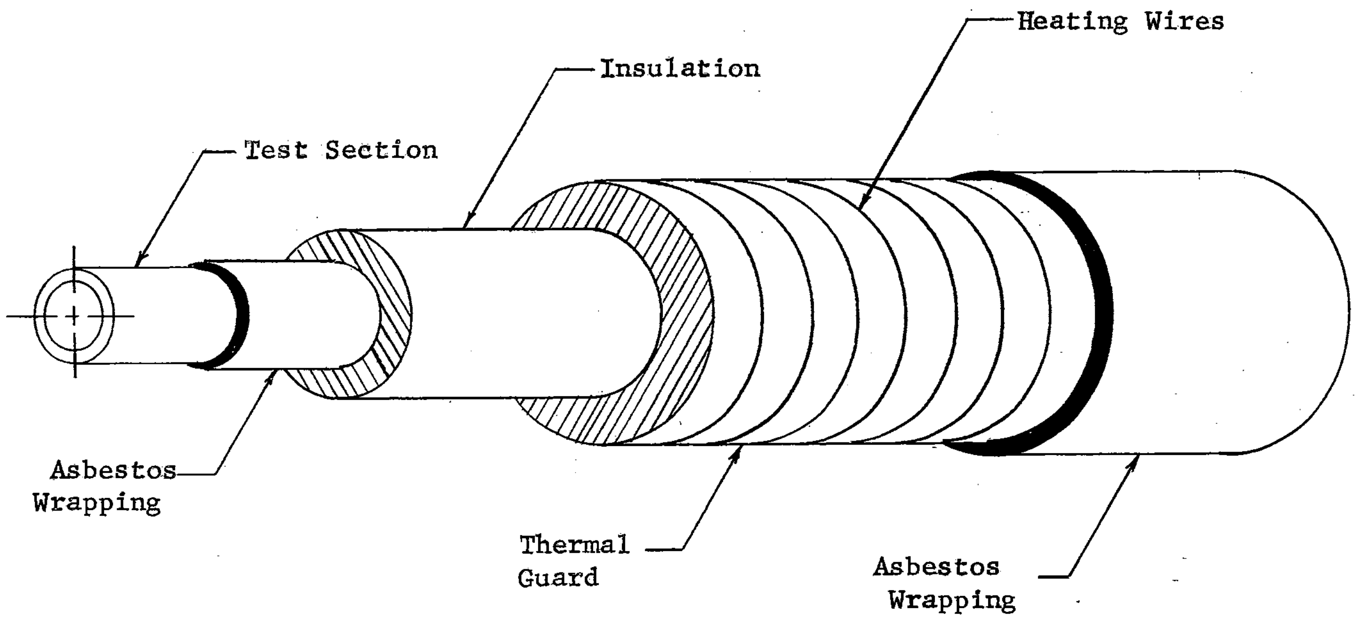


Figure 6. Sketch of Test Section, Insulation, and Thermal Guard

30 minutes prior to turning on the power to the test section. As the conditions in the heat transfer loop are approaching equilibrium, the thermal guard approaches the desired temperature. This temperature is identical to the outside wall temperature of the test section in the boiling region. Figure 7 is a heating curve which indicates the power required for the thermal guard to maintain any given temperature within its range of operation. The deviation of the plotted points from the curve in Figure 7 is caused by the fact that the data for the curve was obtained when various amounts of power were passing through the test section. This deviation was never more than 7% of the desired temperature.

When the heat transfer loop reached equilibrium, fine adjustments were made to the power to the thermal guard so that the temperature under the guard remained identical to the temperature of the wall of the test section. The temperatures indicated on the Brown recorder were used to determine when the thermal guard was at the proper temperature.

It was felt that the thermal guard helped to obtain more accurate data by decreasing the possibility of temperature gradients along the thermocouple wires that were attached to the test section.

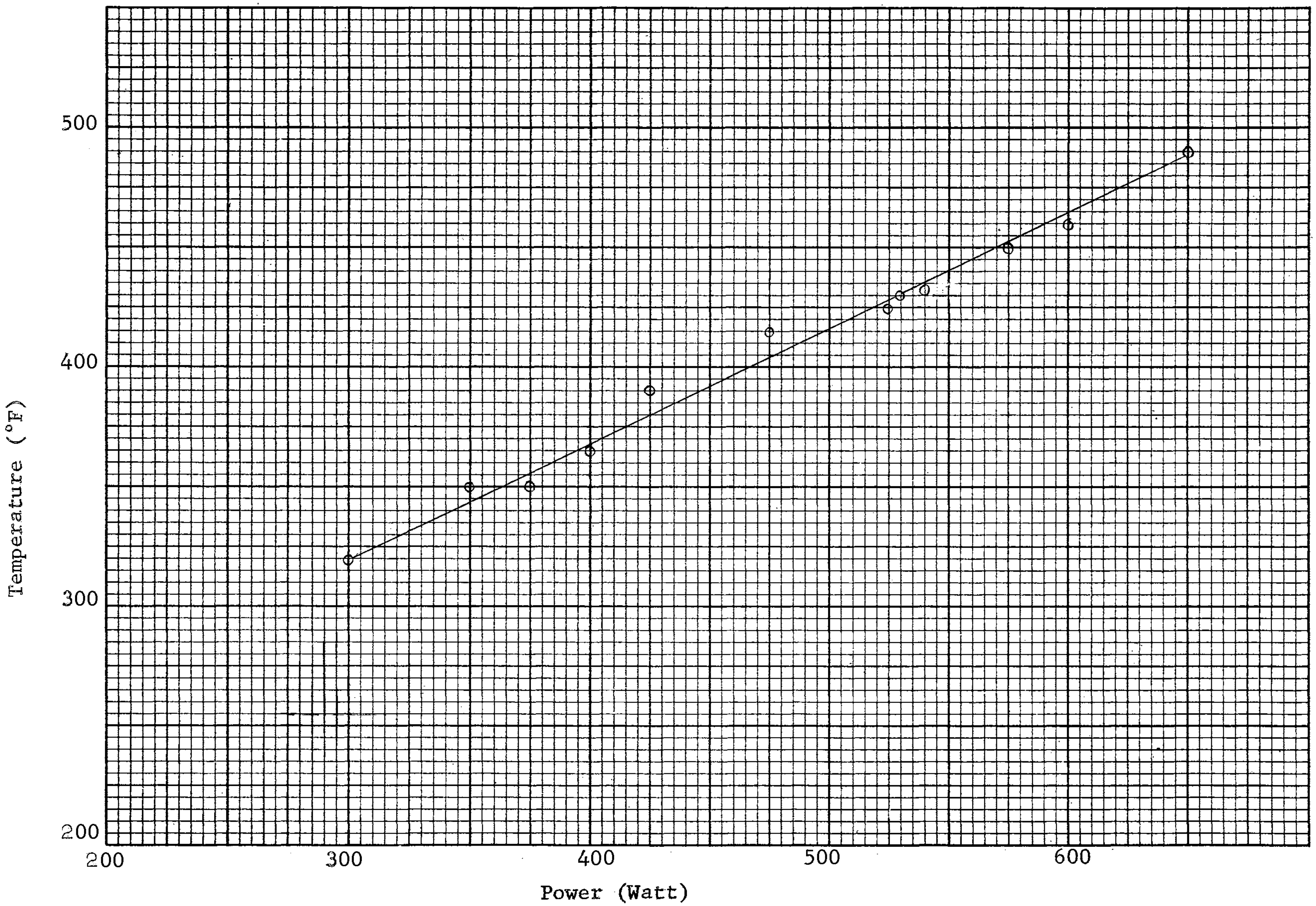


Figure 7. Heating Curve for Thermal Guard

CHAPTER VI

MAIN CIRCULATING PUMP

The main circulating pump was a six-stage progressing-cavity type pump manufactured by Robbins and Myers. This pump was used because of its smooth positive-displacement pumping action, which produced a flow rate nearly independent of system pressure. This characteristic is desirable because an equilibrium condition can be maintained more easily with constant flow rate.

During the process of modifying the loop the pump characteristics were calculated and plotted. These characteristics indicated that the flow rate was no longer independent of system pressure. An inspection of the rotor and stator of the pump revealed that they were no longer in good operating condition. Therefore, the rotor and stator were replaced and again the characteristics were calculated and plotted. The characteristic curves for the last calculation are shown in Figure 8.

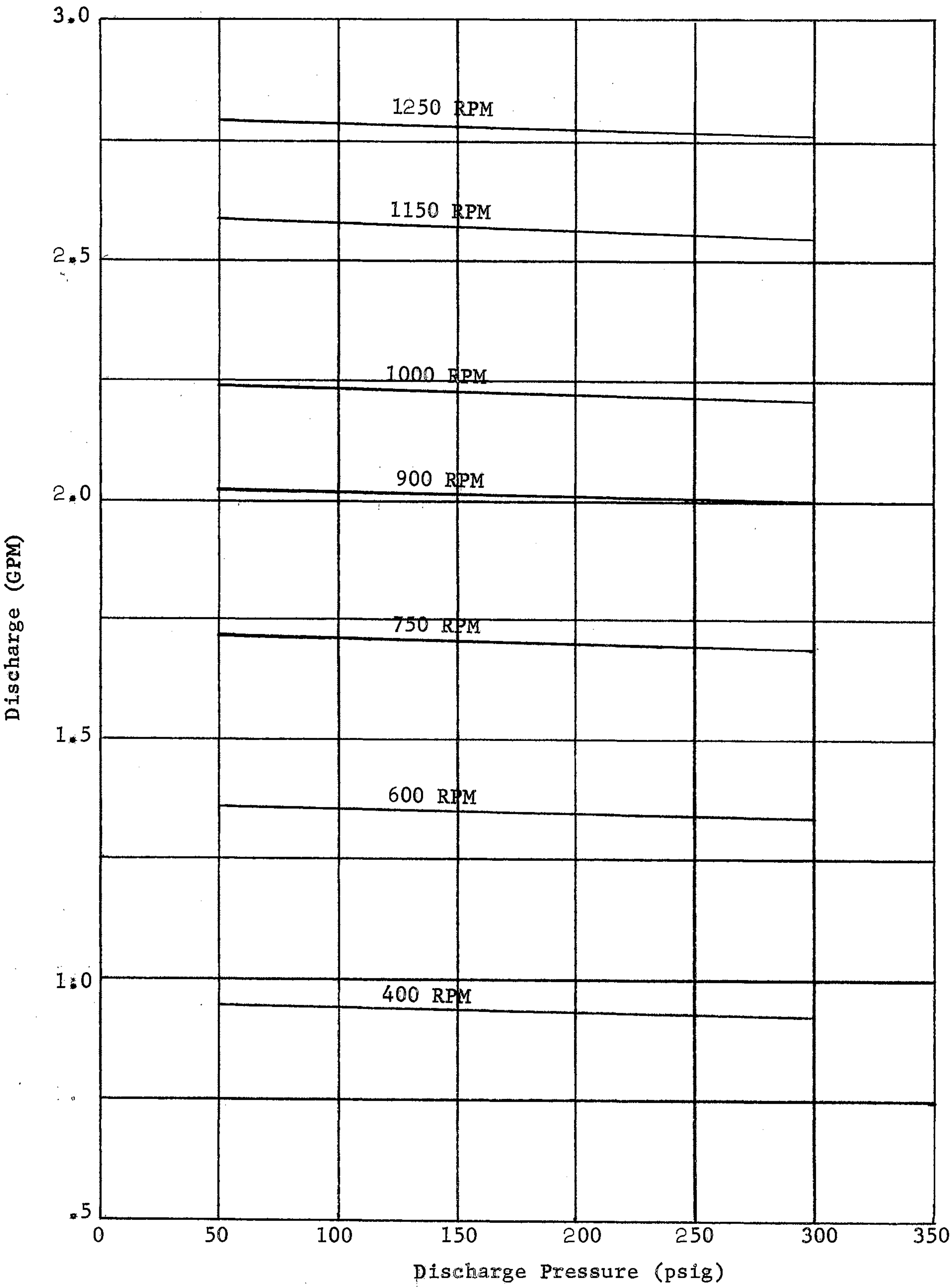


Figure 8. Pump Performance

CHAPTER VII

CALIBRATION OF ORIFICE AND THERMOCOUPLES

Orifice Calibration

The loop is equipped with two sharp-edged orifices, a 0.353-inch and a 0.453-inch, installed in parallel to measure the flow rate through the test section. It is possible to direct the flow through either orifice by use of appropriate valves. Only the 0.353-inch orifice was calibrated, as the flow rates used did not require the use of the 0.453-inch orifice in the binary mixture project.

The basic equation relating rate of flow and manometer level is:

$$W = 0.688 \quad A_o\ K\ E\sqrt{\rho \Delta P}\ ,\ \text{Eq. 1 of (7)} \qquad (1)$$

where:

W = rate of flow, pounds per second

A_o= area of orifice, square inches

K = flow coefficient, dimensionless

E = area multiplier, dimensionless

E = 1 for stainless steel at room temperature (7)

ρ = density, pounds per cubic foot

ΔP = differential pressure across the orifice, pounds per square inch

0.668 = multiplying factor required to make the equation dimensionally correct.

The flow rate was determined by weighing the system fluid for a measured interval of time. This was accomplished by diverting the flow from the exhaust manifold to a container situated on a platform scale. After a minimum of two minutes the flow was returned to the hold-up tank. The time varied with the flow rate and was measured by an electric stop clock to the nearest 0.001 minute. The weight of the fluid was measured by the platform scales that have a maximum error of 0.1 pound.

While the fluid was being diverted into the weighing container, the temperature at the orifice was measured by use of a thermocouple, and the differential pressure across the orifice was measured by the manometer system. Data was obtained for the entire flow rate range of the loop at two systems pressures, 85 and 200 psig. These two pressures were used because they are near the limits of pressures used in the binary mixture project. The flow rate did not change with a change in pressure, which verified the fact that the manometer system was free of air.

The Reynolds number was determined from the equation:

$$Re = \frac{v\ d}{\eta} \tag{2}$$

where

Re = Reynolds number of the orifice, dimensionless

v = velocity, feet per second

d = diameter of orifice, feet

η = kinematic viscosity, square feet per second.

The Reynolds number was calculated for each set of data recorded. A plot of log Re versus K is shown in Figure 9. This plot was favorably compared with Figure 34a in the ASME Power Test Codes-1949 (7).

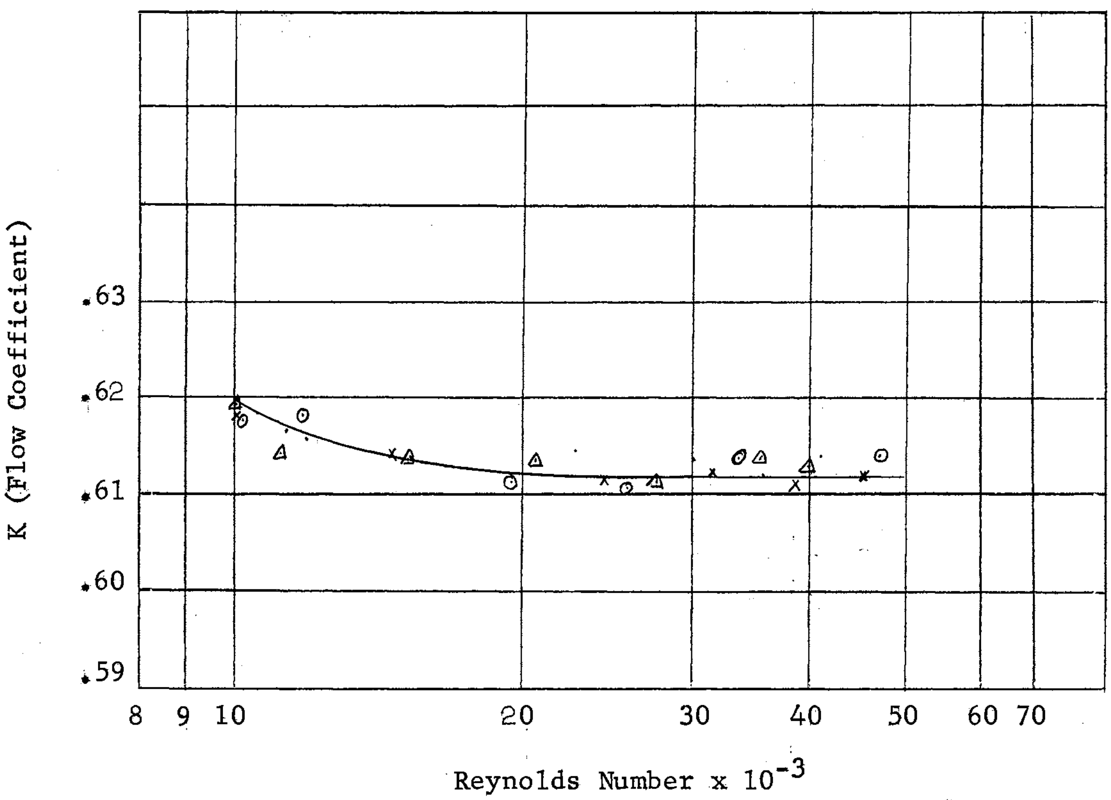


Figure 9. Flow Coefficient Vs. Reynolds Number

The flow coefficient, K, was determined from the equation: (1).

Figure 10 is a logarithmic plot of the flow in pounds per minute versus inches of manometer fluid (specific gravity 1.75).

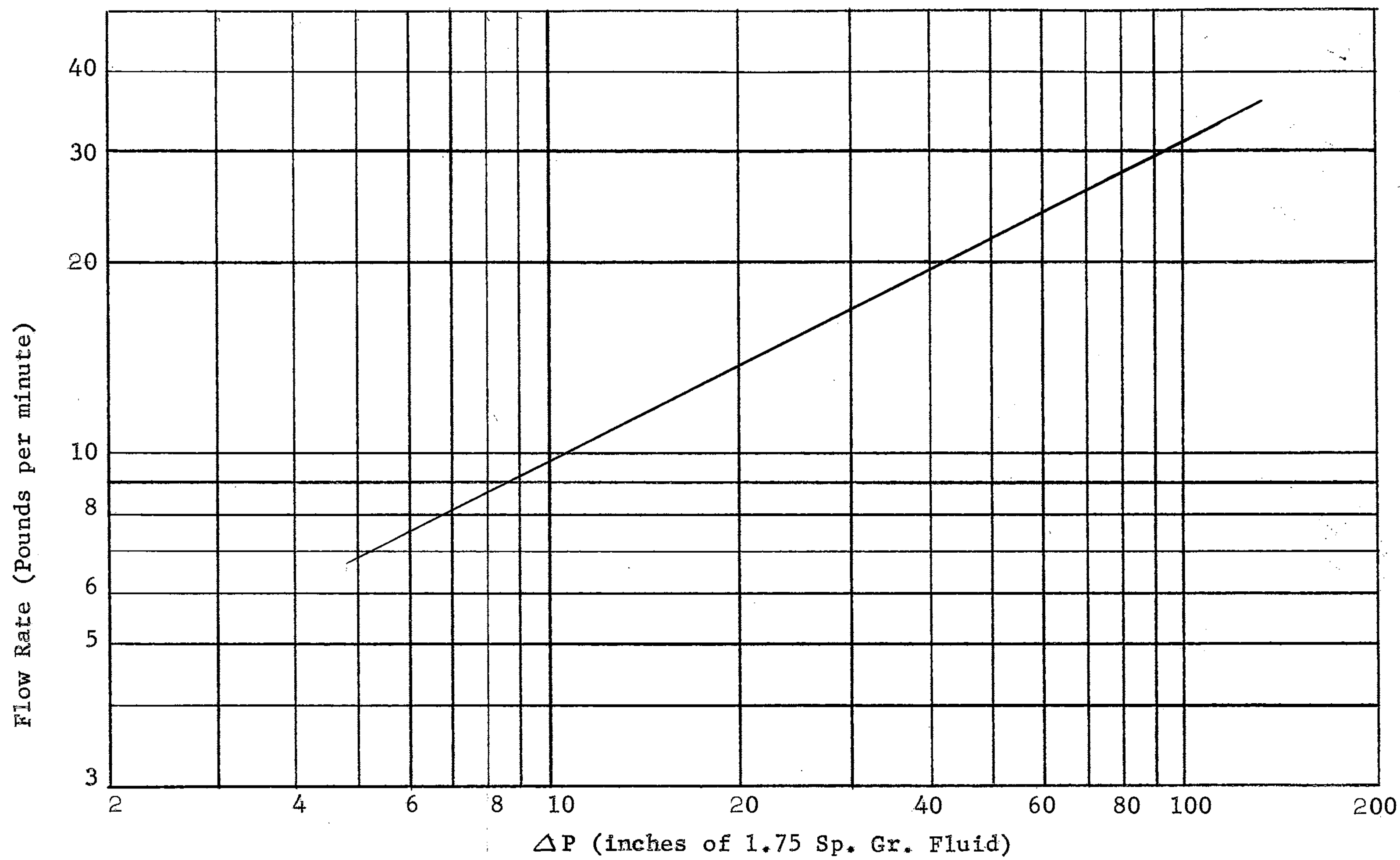


Figure 10. Flow Rate Vs. Manometer Reading

Thermocouple Calibration

The thermocouple calibration consisted of measuring the electromotive force (emf) generated by the iron-constantan thermocouple using junctions at known temperatures. The measured values of emf were compared with values given in the National Bureau of Standards reference tables, for the particular temperatures, to determine the correction. By measuring the emf generated at several known temperatures, it was possible to obtain a calibration curve for use in determining true temperature values from the potentiometer readings.

All emf measurements were made on the Leeds and Northrup Portable Precision Potentiometer used in the binary mixture project.

Calibration data was obtained at the freezing and boiling temperatures of water and the freezing temperatures of pure samples of tin and lead. The metals and corresponding freezing temperatures were certified by the National Bureau of Standards and are listed in Table I. The freezing temperatures listed are those defined by the International Temperature Scale of 1948.

TABLE I

National Bureau of Standards

Freezing Point Samples

Material	Freezing Temperature ^{o}F
TIN	449.42
LEAD	621.32

With the reference junction at the ice-point, the emf generated at the boiling point of water was determined by placing the hot junction in a pyrex tube that was immersed in a hypsometer. The emf was measured during boiling. The boiling temperature at atmospheric pressure was determined from Keenan and Keyes "Steam Tables." (9).

To obtain the calibration data for the thermocouple at the freezing point of water, a clean thermos bottle was filled with crushed ice and water. The thermocouple was inserted into the pyrex tube which was immersed in the thermos of ice-water mixture. The emf was then measured and recorded.

The freezing temperatures of the metal samples were obtained by heating the samples in an electrical resistance crucible furnace designed and built by Clark. (8).

A metal sample was placed into the furnace in a graphite crucible, and the hot junction, protected by a pyrex tube, was inserted into the crucible. As the metal melted, the tube was pushed into the center of the molten mass. The power to the furnace was then shut off and the sample was allowed to cool.

Potentiometer readings of the decreasing emf produced by the cooling samples were taken at intervals of one minute until a constant reading for 15 to 20 minutes was observed. The freezing points were clearly defined by the constant potentiometer readings.

The calibration procedure was repeated at least three times for each freezing point, to insure the validity of the calibration.

The measured emf was converted to temperature (°F) by use of the

International Temperature Scale of 1948. Figures 11 and 12 are the cooling curves for the tin and lead samples, respectively.

A correction curve was determined by comparing the measured temperature for the ice point and steam point of water, the freezing point of tin, and the freezing point of lead. The measured temperatures and corrections are shown in Table II.

TABLE II

Temperature Corrections

Temperature °F	Correction °F
31.45	0.55
209.00	2.10
446.73	2.69
618.60	2.72

These corrections are plotted in Figure 13.

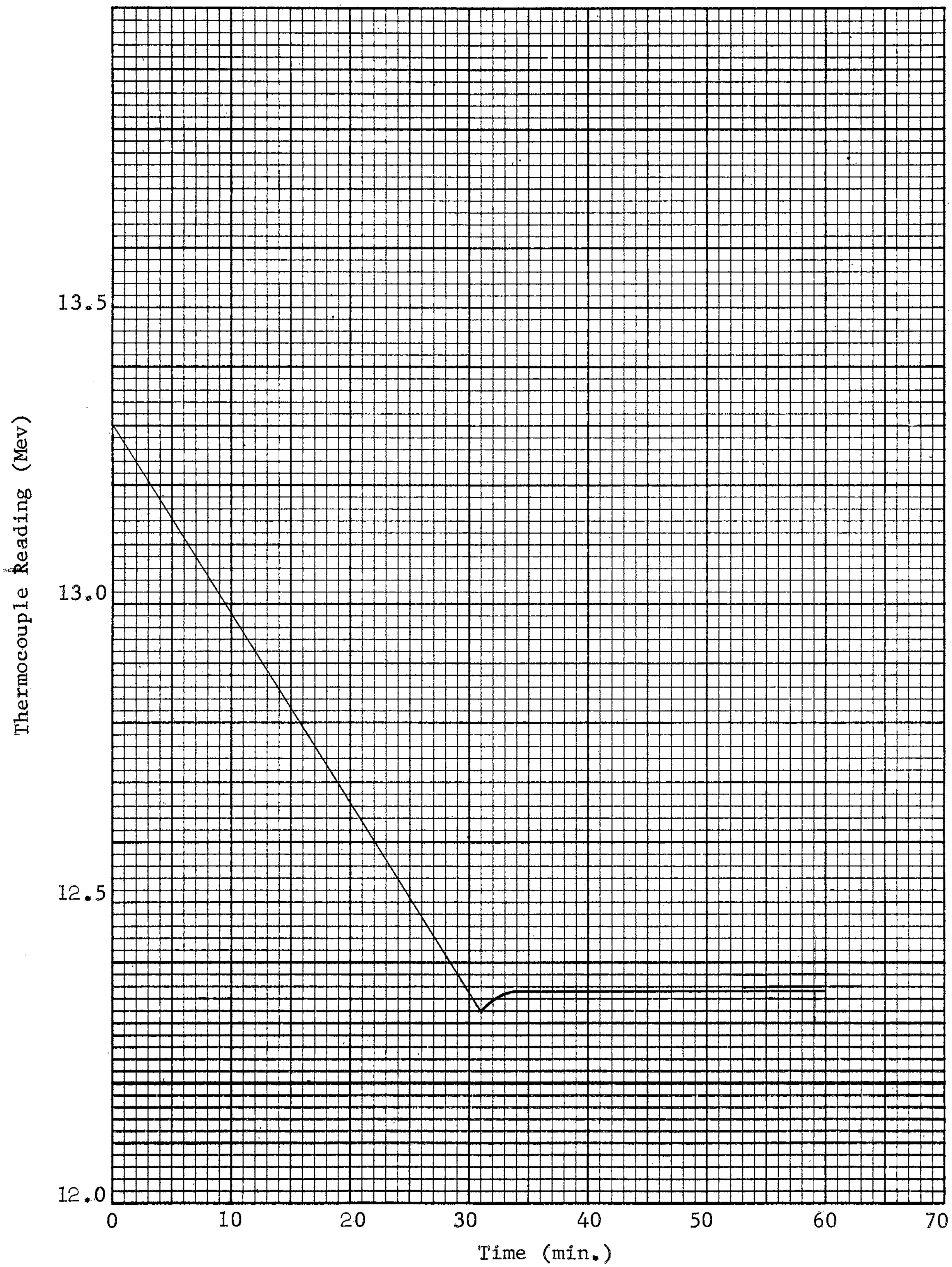


Figure 11. Cooling Curve for Tin Sample

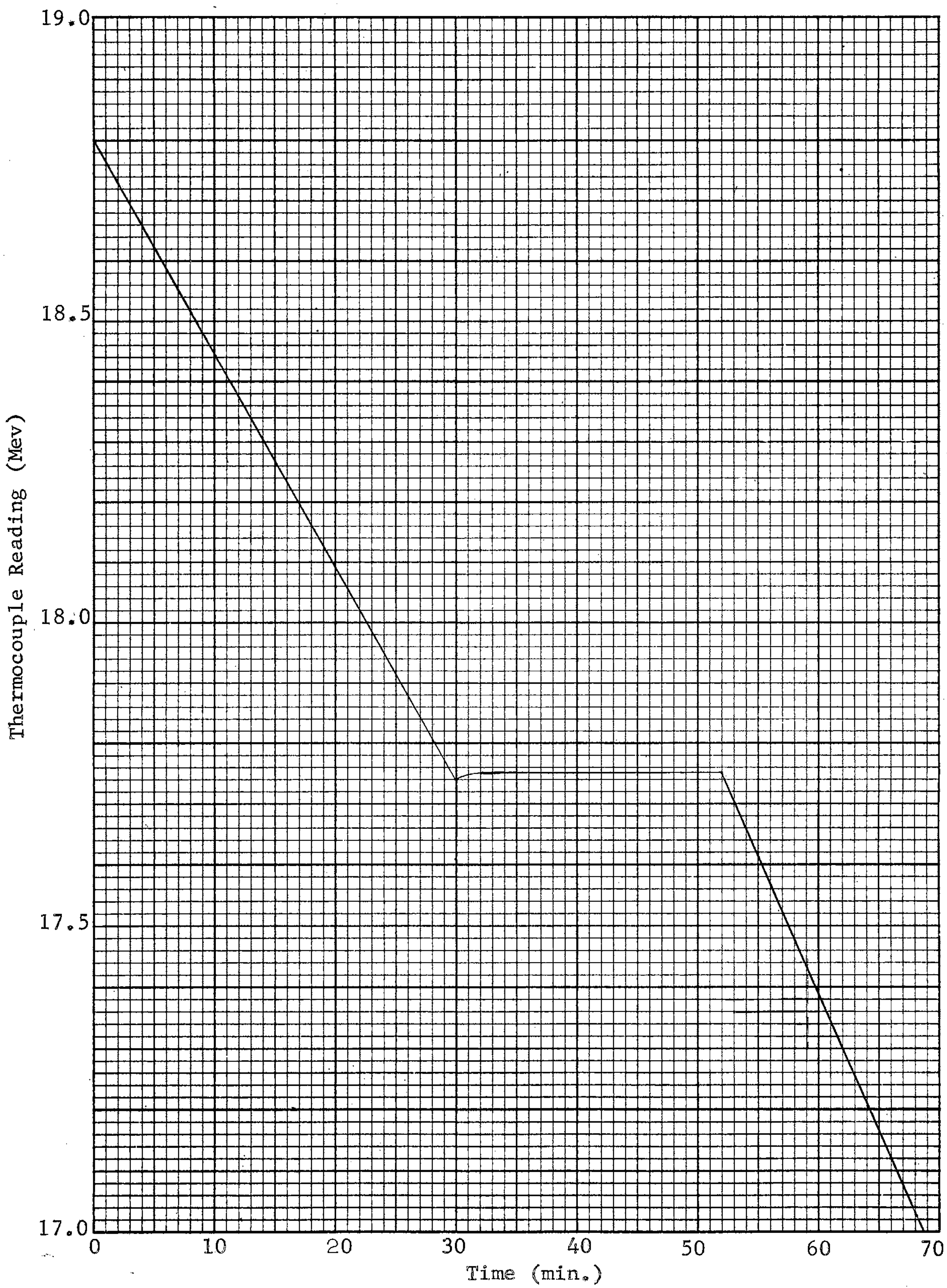


Figure 12. Cooling Curve for Lead Sample

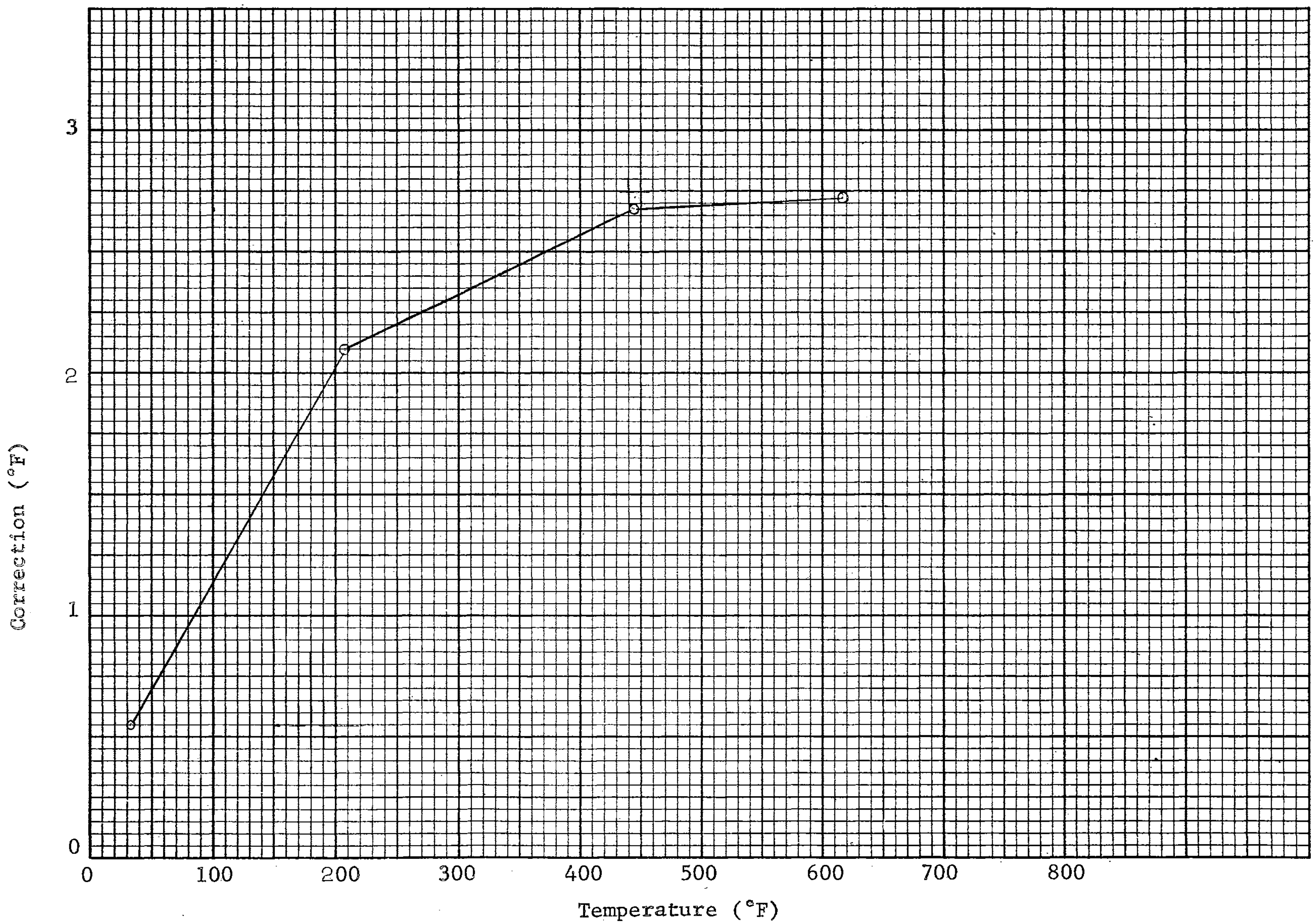


Figure 13. Temperature Calibration Curve

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

From the modifications and additions that were performed on the forced convection heat transfer loop, the following conclusions can be drawn:

1. The potential for obtaining more accurate data pertaining to pressure drop has been improved by:
    a. The addition of a bypass arrangement which allows positive zeroing of the manometers.
    b. The use of a manometer fluid that provides greater readability.
    c. The safety features of the manometer check valves and the manometer piping.
2. The potential for obtaining more accurate data pertaining to heat transfer has been improved by:
    a. A method of attaching the thermocouples to the test section that provides electrical shielding.
    b. The use of a potentiometer which provides a more exact means of measuring temperature.
    c. The addition of a thermal guard which provided an isothermal region for the thermocouples.
3. The operating characteristics of the heat transfer loop improved by the addition of a reliable pressure control system.
4. Estimate of maximum errors:

System pressure	± 0.5 psi
Temperature	± 1/3 °F
Flow Rate	1%
Manometer Measurements	0.1 inches water

In addition to the modifications described in this thesis, the following modifications are recommended:

1. The installation of a needle valve in the system bypass control. Such a valve would allow better control when operating at high pressure.
2. An improved mechanism to control pump RPM. This would allow finer control at all ranges of operation.
3. An individual electric power supply be made available to the heat transfer loop. This would eliminate the fluctuation of power whenever other equipment in the laboratory is in use.
4. The type 304 stainless steel in the heat transfer loop should be replaced by a stainless steel that has better welding characteristics. Welding of type 304 stainless steel produces local heating in the carbide precipitation range, thereby reducing its resistance to corrosion. This corrosion has led to numerous leaks in the heat transfer loop and contamination of system fluid. It is recommended that the type 304 be replaced by type 321 or 347 stainless steel, either of which contain stabilizing elements (columbium and titanium) and are therefore not susceptible to corrosion when welded.

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