



RICE UNIVERSITY

"Coefficient of Viscosity
of Superheated Carbon Tetrachloride"

by

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ABSTRACT

Measurements of the viscosity of superheated carbon tetrachloride were made at various superheats ranging from 0°C superheat to 37°C superheat. The measurements were made in three groups: two isotherms at 82.4°C and 88.3°C, and one isobar at 690 mm Hg.

The three major drawbacks to attaining superheated conditions are vibrations (mechanical shock), impurities, and the maintenance of large volumes of superheated liquid. While the viscometer itself was a simple capillary viscometer, the special procedures and techniques required to attain the necessary superheats entailed the use of high vacuum equipment, liquid degassing systems, a vibration-free table, and controlling systems to maintain the temperatures and pressures within the desired fluctuation limits.

The results obtained show that the viscosity curve for carbon tetrachloride in the superheated regime appears to be a smooth continuation of the curve below the normal boiling point. A curve fit to the experimental data gave the following equation:

$$\mu = -0.9231 + 1.0923\eta + 0.3027\eta^2$$

where

$$\eta = \frac{T_0}{T}, \quad T_0 = 354.55^\circ \text{K}$$

This equation is valid over a temperature range of 70°C to 120°C.

The standard deviation between the experimental data and values

calculated from the given equation is ± 0.004 , which is about 1%. The standard deviation between the fitted curve and previously reported data, which were obtained in a pressurized system, was ± 0.011 , which is about 2.75%.

ACKNOWLEDGEMENTS

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INTRODUCTION

Although the technical literature contains much information concerning the viscosity of liquids, virtually nothing is known with respect to the viscosity of liquids in metastable states. One such neglected metastable state is the superheated state. In 1927 Titani (8) reported viscosity data for several liquids above their normal boiling points, but his data were obtained from a pressurized system. There apparently has been no subsequent interest in this field since no further reports of attempts at measuring superheated viscosities have been located. However, measurements of this sort are of interest, as for example in the investigations of nucleation phenomena, theories of the liquid state, and liquid mixture theories. The purpose of this research project, therefore, was to design, construct, and test a capillary viscometer which could be used to measure the viscosity of superheated liquids, to demonstrate reliable procedures for measuring these viscosities, and to report preliminary results on the test liquid selected, which was carbon tetrachloride.

A superheated liquid will nucleate and boil if a critical number of molecules randomly arrange themselves such that a gas bubble forms. (If less than the critical number of molecules arrange themselves such, the gas bubble formed will spontaneously collapse.) The three major drawbacks to the attainment of superheated

conditions are vibrations, impurities, and the maintenance of large volumes of superheated liquid. Vibrations are likely to cause nucleation because of the many molecular rearrangements which they cause. Impurities may cause nucleation because they act as nucleation sites, especially if the impurity is a gas or nucleates easier than the liquid under study. A large volume of liquid is a drawback because of the greater statistical probability of random nucleation occurring.

The equipment used in this study was designed to insure the attainment of adequate superheats for the test liquid without compromising the experimental precision of the necessary measurements. Since high superheating in liquids requires special procedures and techniques, the amount of equipment required was considerably more than simply a viscometer with a liquid supply and an exit line.

EQUIPMENT

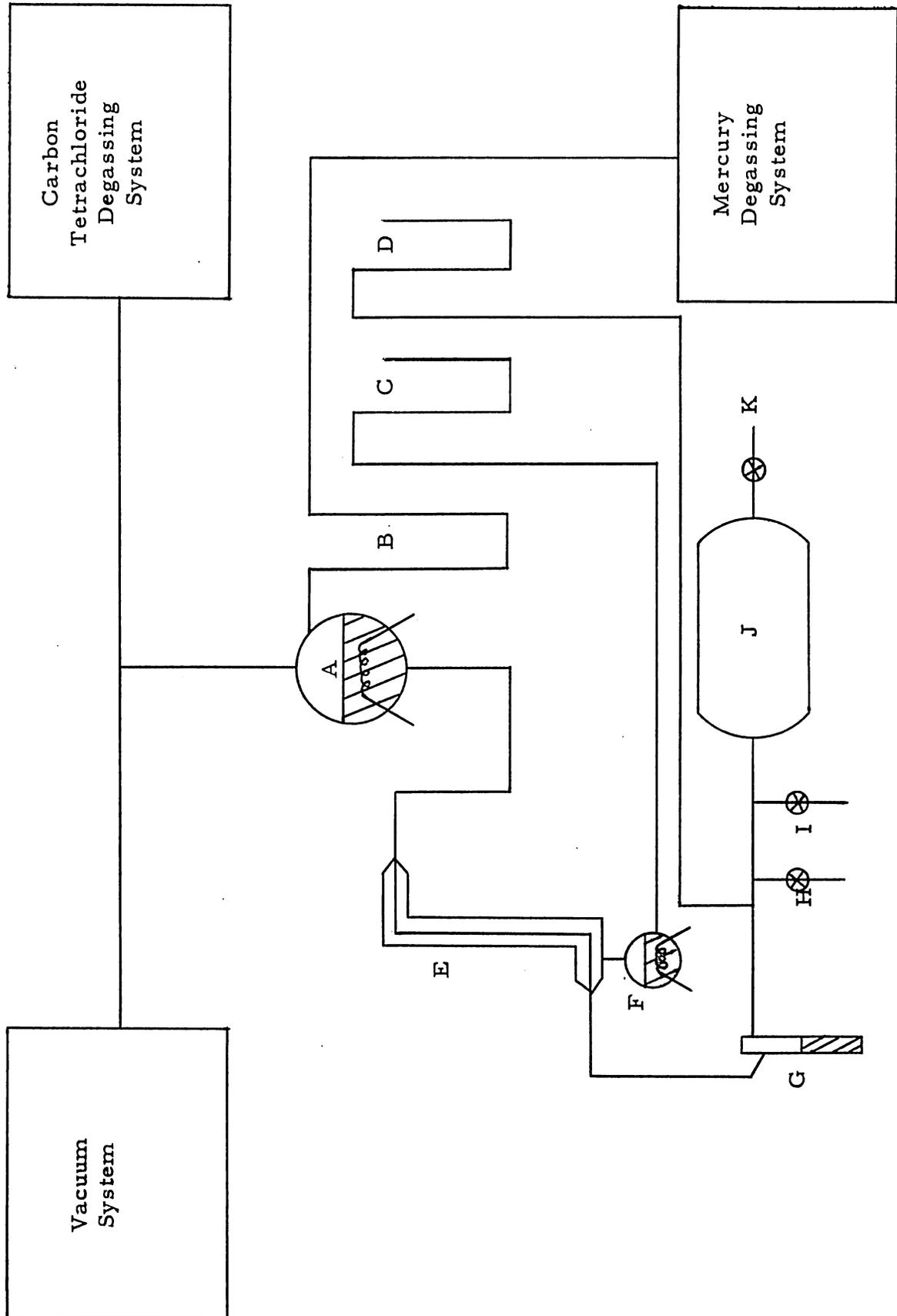
The overall apparatus is readily divisible into five separate sections, in function as well as in physical arrangement. These sections, in order of discussion, are 1) the vacuum system, 2) the carbon tetrachloride degassing system, 3) the mercury degassing system, 4) the viscometer system and 5) the pressure controlling system.

A general schematic diagram of the apparatus is shown on the next page, although the only part shown in detail is the viscometer system. The viscometer system was mounted on a steel table which, in turn, was fastened to shock mountings set into the tops of two cement block walls built especially to support the table. These shock mountings prevented all but low frequency vibrations from reaching the table, thus greatly reducing the possibility of nucleation because of mechanical shock. In addition to the shock mountings, all rigid connections from the table to the outside world were eliminated. The vacuum system, carbon tetrachloride degassing system and mercury degassing system were connected to the viscometer system through glass lines which were sealed off and severed with an oxybutane torch before any attempt was made to superheat the carbon tetrachloride. The pressure controlling system and heater connections were made through electrical cables which did not transmit vibrations.

1) The vacuum system - The vacuum system consisted of a mercury

- A) Carbon tetrachloride reservoir pot
- B) Manometer for upstream pressure
- C) Manometer for water system pressure
- D) Manometer for downstream pressure
- E) Viscometer
- F) Water reservoir pot
- G) Collecting burette
- H) Vacuum line
- I) Air line
- J) Ballast tank
- K) Valve to atmosphere

SCHEMATIC DIAGRAM OF APPARATUS

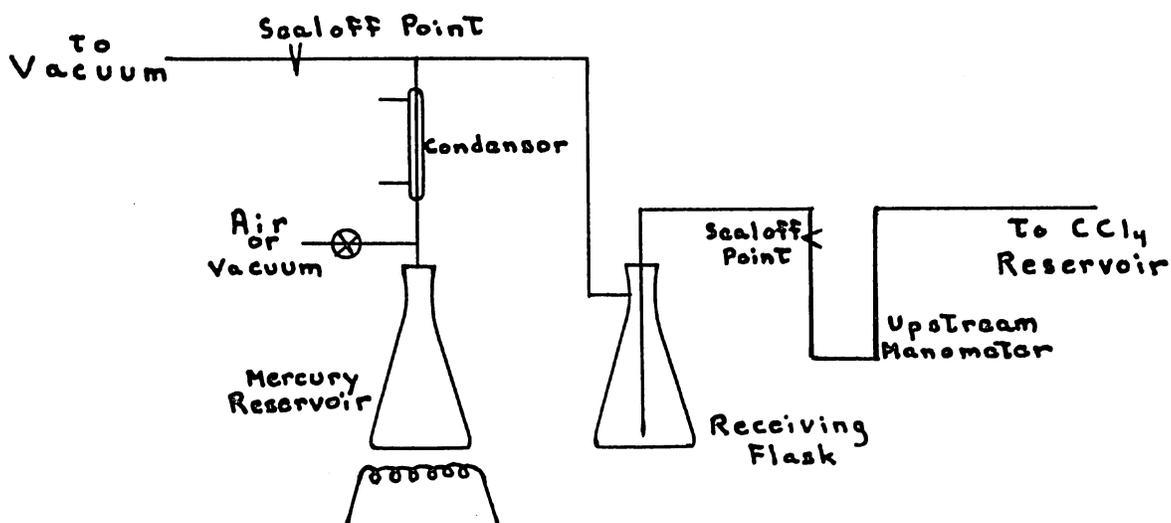


diffusion pump in series with a two-stage mechanical forepump. There was an ionization gauge located between the pumps and the viscometer system so that the pressure in the viscometer system could be monitored. There was also a thermocouple gauge located just beyond the forepump to measure the forepump pressure. The mercury diffusion pump was isolated from the rest of the vacuum system by two liquid nitrogen cold traps.

2) The carbon tetrachloride degassing system - This system consisted of a large pot of carbon tetrachloride mounted at the base of a distillation column packed with glass beads. Above the distillation column was a sonic orifice with the downstream side of the orifice attached to a vacuum line. A heating coil below the carbon tetrachloride pot vaporized the liquid up into the distillation column. The column was operated essentially at total reflux, but gaseous impurities (as well as some carbon tetrachloride vapor) were drawn through the sonic orifice. Starting with spectroquality liquid, degassed carbon tetrachloride of extremely high purity could be obtained with this system. (The sonic orifice employed consisted of a short length of very small diameter capillary tubing.)

3) The mercury degassing system - In the manometer which measured the pressure upstream of the viscometer, the mercury was in direct contact with the carefully degassed carbon tetrachloride.

Therefore this mercury was also degassed. The mercury degassing system is shown in the following sketch.



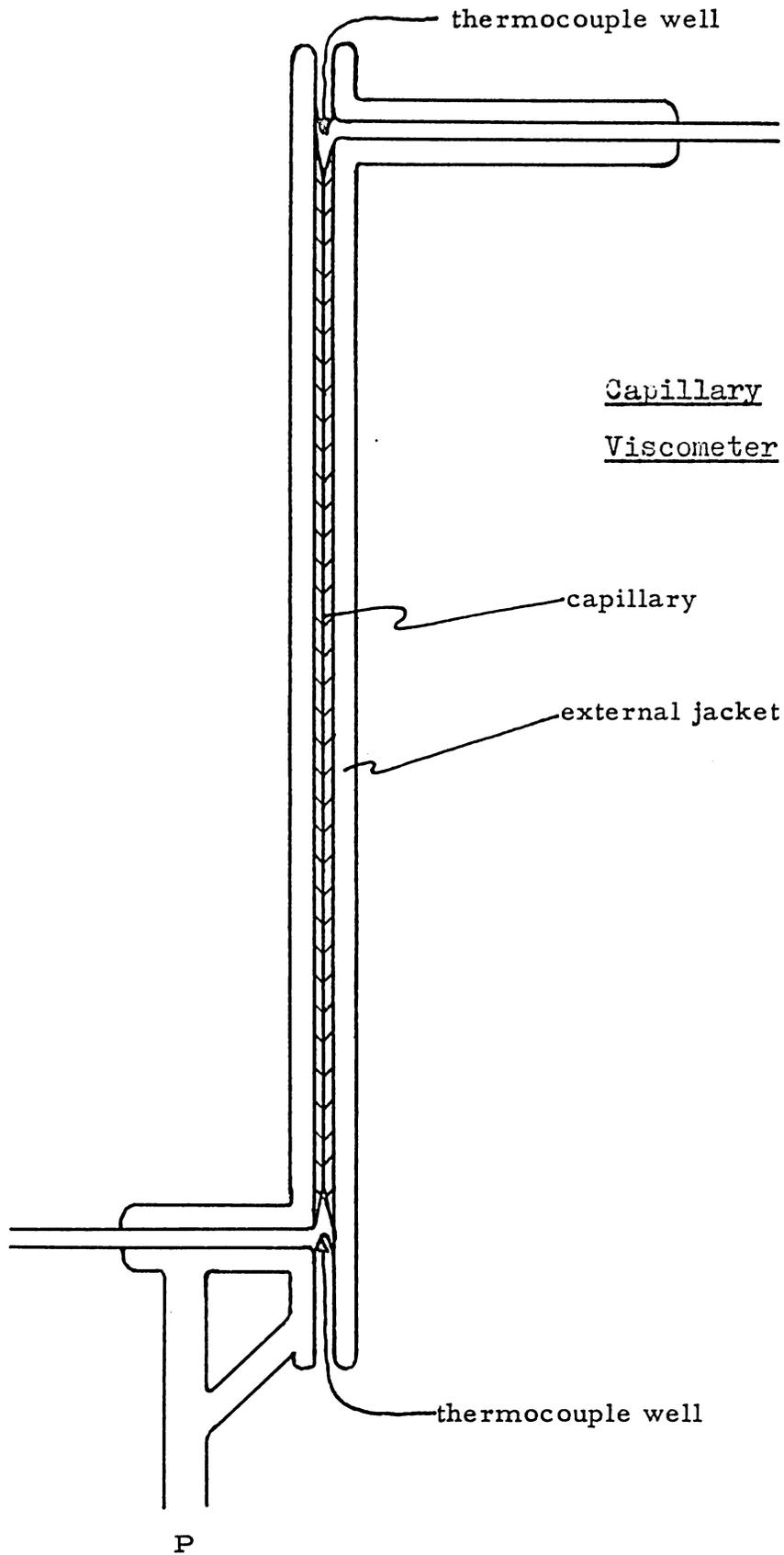
Initially the mercury was in the flask above the heater. With the heat turned on low, the mercury was vaporized up into the condensor where it condensed and returned to the mercury reservoir. Any gaseous impurities were pulled out of the system by the vacuum pumps. After this had continued for a few hours, the condensor water was turned off and the heater was turned up so that the vaporized mercury was driven over into the receiving flask where it condensed. When sufficient mercury was driven over to cover the entrance of the tube leading to the manometer, the heat was turned off. After the mercury had cooled, it was driven over into the manometer by sealing off the line to the vacuum system and pressurizing the receiving flask.

4) The viscometer system - A sketch of the viscometer itself is

shown on the next page. It consisted of a section of capillary tubing with entrance and exit tubes. The capillary, along with portions of the entrance and exit lines, was surrounded by an external jacket. The viscometer was maintained at the desired temperature by film condensation of steam in the outer jacket. Carbon tetrachloride at its saturation temperature entered the jacketed section of the entrance line above the capillary. The length of this jacketed section was calculated using the Graetz solution to the steady state flow problem (5) so as to insure that the liquid entering the capillary would always be at the desired superheat. Similarly the length of the jacketed section of the exit tube was calculated so that no thermal gradient could possibly extend back into the capillary. Thermocouple wells were located at the entrance and exit of the capillary so that these temperatures could be measured. (Monitoring the temperature during an entire run showed that it remained constant throughout a run.)

The entire viscometer system and external connections were made of glass since it was the only substance non-reactive with carbon tetrachloride which could be rigorously enough degassed to insure that there would be no contamination of the liquid by substances adsorbed on the walls of the viscometer system.

As mentioned previously, all rigid connections from the outside world to the viscometer system were severed before any attempt was made to superheat the carbon tetrachloride. This meant that for any series of runs, a supply of carbon tetrachloride had to be



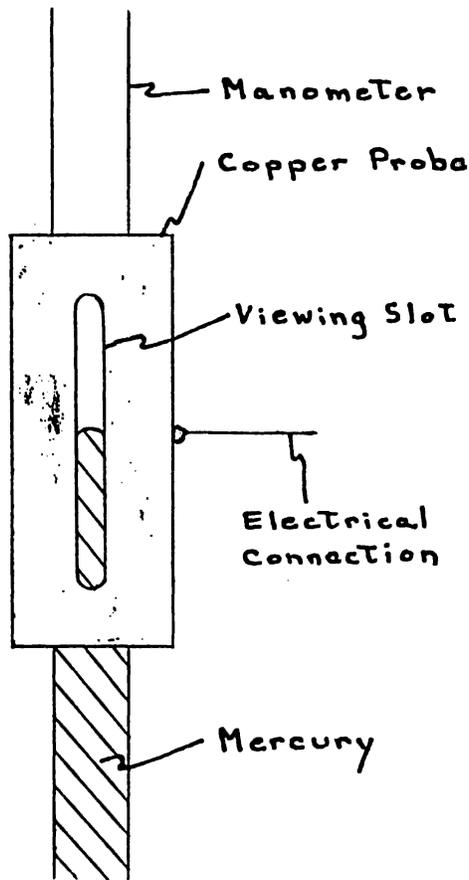
available on the table. This section of the apparatus therefore consisted of three pieces of equipment: a carbon tetrachloride reservoir pot, the viscometer, and a collecting burette beyond the viscometer. The reservoir pot was housed in an insulated cylinder which was maintained at the saturation temperature of the liquid. From the reservoir pot, the liquid flowed into the viscometer, which was supported in a second insulated cylinder. The liquid then moved from the viscometer into a collecting burette at room temperature. This burette was a true-bore tube in which flow rates were obtained by measuring the rate of rise of a liquid meniscus.

A reservoir pot for generating the saturated steam used to thermostat the capillary tube was attached to the viscometer at the point "P" in the drawing. The water from this pot was boiled up into the outer jacket of the viscometer where it condensed and ran back down into the reservoir pot. The temperatures in the cylinders housing the viscometer and reservoir pot were maintained at the desired levels by means of heaters either wrapped around the cylinders or mounted within the cylinders.

The viscometer system was set up so that the glass line leading to the collecting burette had a sort of breakoff valve which had to be opened for the initial run. Subsequently the flow was stopped between runs by using liquid nitrogen to freeze off a u-tube located just before the collecting burette. Flow was effected by setting the upstream

pressure at a higher value than the downstream pressure.

5) The pressure controlling system - There were three pressures in the viscometer system which needed to be controlled. These were the pressure upstream of the viscometer, the pressure downstream of the viscometer, and the pressure in the water system which maintained the outer jacket of the viscometer at the desired superheat. The pressure downstream of the viscometer was controlled by having air and vacuum lines attached to the vapor section of the collecting burette and using these to set the pressure. A large-volume ballast tank hooked into this system served to damp out any pressure fluctuations which might have occurred. There was no back diffusion of impurities into the viscometer between runs due to the frozen-off u-tube. All three of the viscometer system pressures were measured with Torricellian manometers (in which the pressure on the manometer is measured against a vacuum in the mercury leg of the manometer). The upstream and water pressures were controlled by means of capacitance circuits on the mercury legs of the manometers. These capacitance circuits operated through two probes located on the mercury leg of each manometer. The lower probe was located at the bottom of the mercury leg so that the mercury column was always through it. The upper probe was located at the point on the mercury leg where the pressure was to be controlled. A drawing of the upper probe is shown at the top of the next page. Rather than depending on



making and breaking a direct electrical contact, these probes depended on a buildup of voltage due to the capacitive action between the mercury and the copper probe, with glass as the dielectric between the two. As the top of the mercury column rose in the upper probe, the voltage across this probe built up. When this voltage reached a preset value corresponding to the point of

desired pressure control, it caused an electronic switch to be thrown. This switch activated an electromagnet which threw a double action relay from the rest position to the activated position. This relay was hooked up in such a way that when it was in the rest position, there was a small resistance in series with a heating element located in the carbon tetrachloride reservoir pot (or water reservoir pot); and when it was in the activated position, there was a large resistance in series with the heating element in the reservoir pot. When the pressure rose in the system, the mercury rose and completed the capacitance circuit. This activated the electromagnet which in turn activated the

relay. The activated relay hooked the larger resistance in series with the heating element so that less power was delivered to the reservoir pot. This caused the pressure to drop and thus the mercury meniscus to fall. The dropping of the mercury broke the capacitance circuit, the electronic switch turned off the electromagnet, and the deactivated relay hooked the small resistance in series with the heating element. More power was delivered to the reservoir pot, causing the pressure to rise, etc.. This cycle maintained the pressure at the desired level by repeating itself rapidly over and over.

PROCEDURE

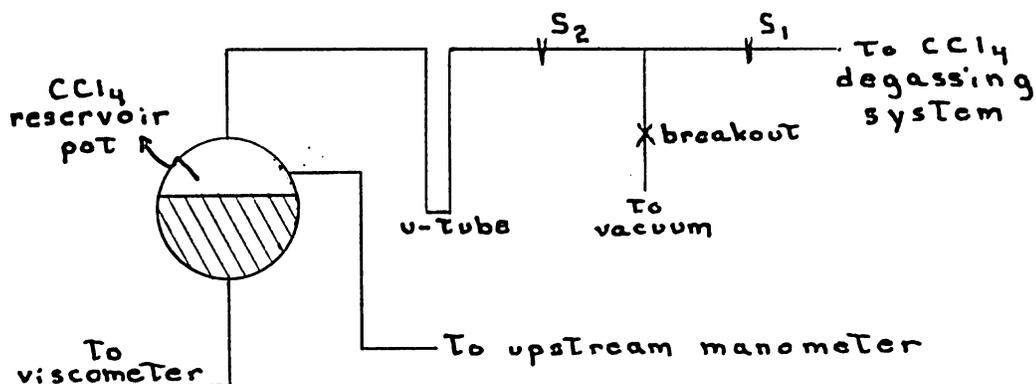
The first stage in preparing the apparatus was the degassing of the viscometer system. This was accomplished by heating the system to about 400°C while maintaining it at an extremely low vacuum on the order of 10^{-6} or 10^{-7} mm Hg. In this way most of the impurities deposited and adsorbed on the glass walls would be driven off and removed from the system. This combination of low vacuum and high temperature was maintained for about a week. With about two days of viscometer system degassing to go, the carbon tetrachloride degasser was set in operation. At about this time the mercury degasser was also started. After the mercury degasser had run for about a day, the mercury was driven into the receiving flask, which took about another day. Thus the viscometer system, the carbon tetrachloride, and the mercury were all ready at the same time. During the degassing of the mercury and carbon tetrachloride, all glass lines in the viscometer system which were not maintained at 400°C within the insulated cylinders were repeatedly flamed out by hand with an oxybutane torch.

Next, the degassed mercury was charged into the upstream manometer as described previously. After sufficient mercury had flowed into the manometer, the mercury degassing system was again evacuated; and the mercury leg of the upstream manometer was sealed off under vacuum to obtain a Torricellian manometer.

The system side of this manometer was heated to obtain an interface between carbon tetrachloride vapor and mercury because this would simplify the equations used in calculating the results. This heating was effected by encasing the carbon tetrachloride leg of the manometer in a copper tube around which heating wire was wrapped. Thus the manometer could be maintained at a high enough temperature so that no carbon tetrachloride would condense within the manometer. This heating coil was now activated since the next step was to charge the viscometer system with carbon tetrachloride. Since carbon tetrachloride and mercury tend to interact, a carbon tetrachloride-mercury interface becomes very indistinct and undefinable after a period of time. For this reason a one-shot glass breakout valve opened by a glass-encased, magnetically-moved piece of steel rod was installed in the carbon tetrachloride leg of this manometer. Thus the two substances could be kept separated as long as necessary.

While the mercury was being charged, the high degas temperature in the insulated cylinders was reduced below the boiling point of carbon tetrachloride in preparation for charging the viscometer system. After this had been done, the pressure in the carbon tetrachloride degassing system was built up by increasing the power input to the degasser heater. Up to this time the carbon tetrachloride degassing system was separated from the viscometer system by another one-shot glass breakout valve. When the cylinders were cool and the

pressure in the degasser system had built up, the breakout valve was opened. The high pressure in the carbon tetrachloride degassing system drove carbon tetrachloride vapor into the viscometer system, where it condensed. After a sufficient amount of carbon tetrachloride had collected in the viscometer system reservoir pot, the glass line leading to the carbon tetrachloride degassing system was sealed off with the oxybutane torch. (In order to avoid contaminating the viscometer system by decomposing any carbon tetrachloride in the line leading to the liquid degasser, this sealoff was accomplished as



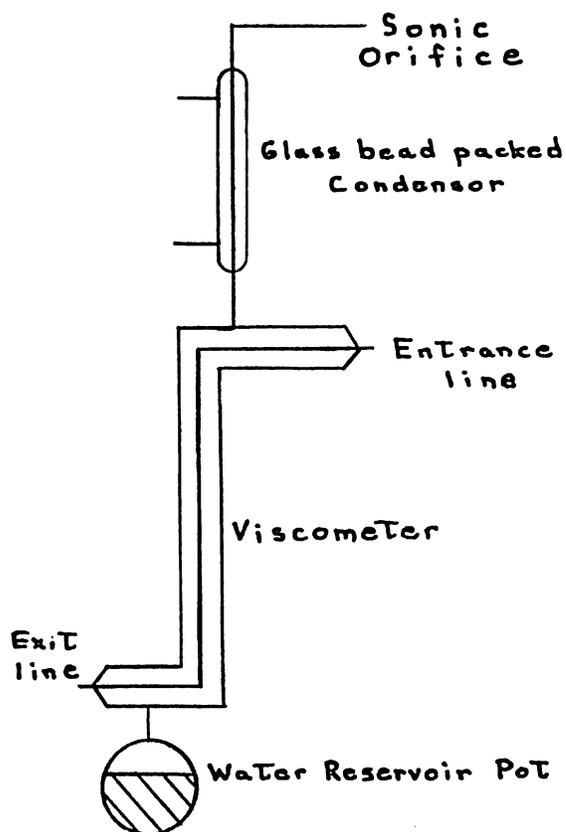
follows. First a u-tube (see diagram) located in the degasser line was frozen off with liquid nitrogen. Next the line leading to the degasser was sealed off at S_1 . There was a line leading to vacuum hooked into the degasser line and closed with a breakout valve. This breakout valve was now opened so that all of the carbon tetrachloride vapor between S_1 and the frozen u-tube could be evacuated. After evacuation, the line was sealed off at S_2 , this time under vacuum.

The u-tube was then unfrozen.)

The next step was to fill the manometers which measured the pressure downstream of the viscometer and the pressure of the water system. (Clean mercury was used for this purpose, but this mercury was not degassed. Degassed mercury was supposedly unnecessary in these manometers since there was no possibility of contamination of the carbon tetrachloride. Later it became apparent that degassed mercury should have been used because the carbon tetrachloride-mercury interface where the mercury was not degassed became nearly unreadable whereas the interface where the mercury was degassed was still sharp and clear.) After these manometers were filled, the mercury legs were evacuated and sealed off under vacuum to obtain the desired Torricellian manometers. These manometers were calibrated against a continuously evacuated manometer both before and after the set of runs to check for leakage into the manometers during the sealoff and for leakage into the manometers over a period of time. There was apparently no leakage with time, but there was a slight amount of gas present in the mercury legs. This may have been due to a slight leakage during the sealoff, but there is also the possibility that some gas dissolved in the mercury found its way into the evacuated legs.

The water used in the outer jacket of the viscometer was also degassed. This was done with the water already in its reservoir pot

by attaching a condenser vertically to the external jacket of the viscometer entrance tube (see diagram). This condenser was packed



with glass beads and evacuated through a sonic orifice. Using the heater in the water reservoir pot, water was vaporized up through the viscometer jacket into the condenser, which acted as a distillation column at total reflux. When the water was sufficiently degassed, the condenser was sealed off under the vapor pressure of the pure

water and removed from the outer jacket of the viscometer.

Now all external connections to the table were severed, and the viscometer system was ready for use. The procedure for any one run was as follows.

- 1) Set and maintain the pressure in the water system at the desired level using the electronic pressure controlling system. Since this pressure is the vapor pressure of the pure water, this is in effect

setting the temperature in the outer jacket of the viscometer.

2) Set and maintain the pressure upstream of the viscometer using the electronic pressure controlling system. Since this manometer is attached to the vapor section of the reservoir pot, the pressure being controlled is the vapor pressure of the carbon tetrachloride in the reservoir pot.

3) Using the internal and external heaters of the insulated cylinders, set the temperature in the reservoir pot cylinder to the temperature corresponding to saturation for carbon tetrachloride at the pressure which was set in step 2. Set the temperature in the viscometer cylinder to the superheat temperature corresponding to the temperature of the water in the external jacket of the viscometer.

4) Starting with the pressure measured upstream of the viscometer, calculate the value which the downstream pressure should have in order to give the desired pressure drop across the capillary section of the viscometer. Using the air and vacuum lines, set this pressure at the correct value. (There was no electronic control on this pressure for two reasons. One was that there was no particular place to install a heater for the electronic switch to control. The other was that there was no reason for the pressure to change. Any slight

changes which might have tended to occur would have been damped out by the ballast tank hooked into the system.)

5) Make and record a final measurement of the upstream and downstream pressures. (These pressure measurements were made by using a cathetometer to measure the net heights of the mercury columns in the manometers.)

6) Record the temperatures at the top and bottom of the capillary and the temperature of the collecting burette. (The temperatures for the capillary were read using a three place potentiometer and thermocouples located at the ends of the capillary tube. The burette temperature was read from a thermometer located just outside the burette.)

7) Unfreeze the u-tube and allow flow to start. (There were actually two parts to this step. Before step 3, the dewar flask containing liquid nitrogen was replaced by a dewar flask containing a mixture of acetone and dry ice. The acetone and dry ice mixture only covered the bottom half inch or so of the u-tube. In this way most of the u-tube could be warmed to room temperature by the time that the final unfreezing arrived. In the early runs where the unfreezing was limited to simply removing the dewar of liquid nitrogen, there was

not enough time or carbon tetrachloride to allow the u-tube to reach room temperature. As a result the expansion effects of the carbon tetrachloride and u-tube as they warmed up from the extremely low liquid nitrogen temperature caused the data to be inconsistent.)

8) Measure the rate of rise of the carbon tetrachloride meniscus in the collecting burette. (This was done using the cathetometer and stopwatches. Two measurements were always made to check the consistency of the flow rate data. The rate of rise measurement could be converted directly to volumetric flow rate because the true bore burette was calibrated in cubic centimeters of volume per centimeter of length.)

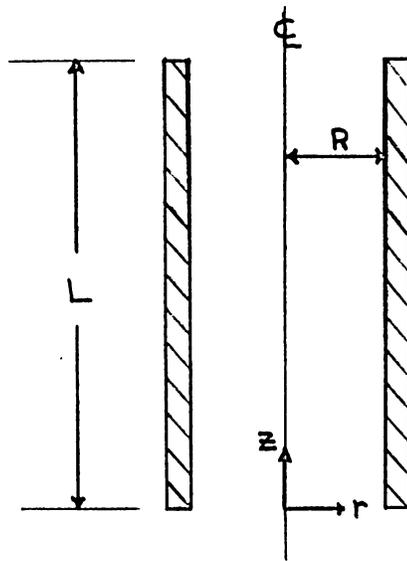
9) Stop flow by freezing the u-tube with the liquid nitrogen dewar.

10) Measure and record the upstream and downstream pressures to be sure that there was no significant drift during the run.

11) Record again the capillary temperatures to be sure that they did not change. Also record the reservoir pot temperature. (There was a thermocouple located just outside of the reservoir pot in the insulated cylinder.)

CALCULATIONS

There is only one equation necessary to calculate the viscosity from the data taken in a capillary viscometer. This is the Hagen-Poiseuille law for steady state, laminar flow in a straight, cylindrical pipe. The derivation of this equation is quite straight forward and simple, and so is not given here. It may be found in Bird, Stewart & Lightfoot, Transport Phenomena , pages 42-47.(1) The form of the equation used in this experiment states that, given a vertical, cylindrical tube with coordinate system as shown in the



accompanying diagram, the relationship between the volumetric flow rate and the forces on the system can be stated as

$$Q = \frac{\pi (P_L - P_0) R^4}{8\mu L}$$

where

$$Q = \text{volumetric flow rate} - \text{cm}^3$$

R = radius of pipe - cm

L = length of pipe - cm

μ = viscosity - poises

$\rho = P + \rho gz$

P = pressure - dynes per cm²

ρ = density - gm per cm³

g = gravitational acceleration - cm per sec²

z = vertical distance - cm

For this experiment in particular, the equation was modified to read

$$Q = \frac{A}{\mu} (\Delta P + \rho L)$$

where $A = \frac{\pi R^4}{8L}$ and ΔP is the pressure drop across the capillary. In this way several runs could be made at temperatures below the normal boiling point and a value of "A" calculated from known viscosity information. This eliminated the need for accurately determining "g" and accurately measuring "R" as well as taking into account any small peculiarities of the system.

There are certain restrictions on the use of the Hagen-Poiseuille law due to assumptions made in the derivation. These restrictions are (1):

- 1) laminar flow (Re less than about 2100)
- 2) incompressible flow (constant density)
- 3) steady state flow
- 4) neglect of end effects (This means that the distance "L"

in the Hagen-Poiseuille law is measured exclusive of the entrance length of tube required for development of the parabolic velocity profile.)

- 5) the fluid behaving as a continuum
- 6) no slip at the wall.

The flow situation which prevailed in this experiment easily fits all of these requirements, although perhaps some discussion is in order with respect to the neglect of end effects. According to Bird, Stewart & Lightfoot, the entrance length required for the development of the parabolic velocity profile is on the order of $0.035D(Re)$. For this study, $0.035D(Re)$ under flow conditions equals approximately 1.5 millimeters, as compared with an overall capillary length of 300 millimeters. The correction for end effects is thoroughly discussed in the Ph.D. thesis of J.G. Giddings (3). A calculation of the correction factor showed it to have an effect of about 0.01% on the experimental results. On the basis of the above calculations, the end effects were ignored as being virtually non-existent as compared to any experimental error.

Calculations were also made to determine how long it was necessary to wait for the system to reach steady state under flow conditions. This is the solution to the equation for unsteady state, laminar flow in a circular tube. This problem is treated in detail in

Bird, Stewart & Lightfoot, pages 126-130 (1); and graphs of the solution are given. For this system calculations showed that the time required to reach 98% of steady state was about 0.047 seconds.

RESULTS AND DISCUSSION

Titani (8) gives viscosity data for carbon tetrachloride over a temperature range of 20°C through 180°C. The values given above the normal boiling point of carbon tetrachloride were obtained by measuring the viscosity of the liquid at greater than atmospheric pressures. The graph on the next page shows that portion of his data which falls within the range of interest of this study.

The results obtained in this experiment are tabulated on page 27 as well as being shown on the graph on the next page. In order to smooth the data obtained in this study, a least squares fit was made to the curve

$$\mu = a + b\eta + c\eta^2$$

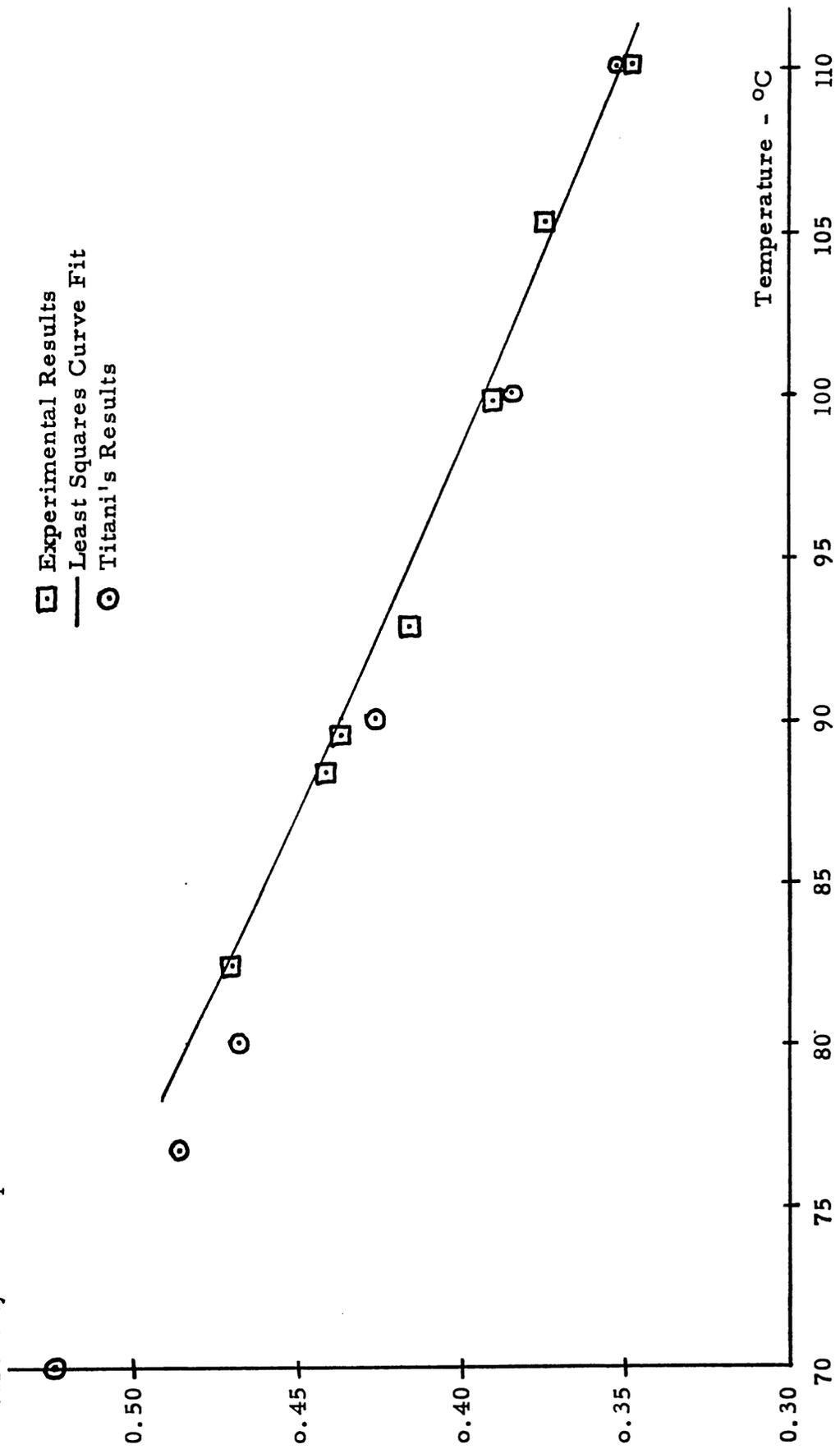
where $\eta = \frac{T_0}{T}$, T_0 being a constant which was assigned the value of 354.55°K in order to keep values of η near unity. Calculation of the constants gave the equation

$$\mu = -0.9231 + 1.0923\eta + 0.3027\eta^2$$

which is valid over the temperature range 70°C to 120°C. The standard deviation between the experimental data and the viscosity values calculated from the fitted curve is ± 0.004 , which is about 1%. The standard deviation between Titani's data and corresponding values calculated from the fitted curve is ± 0.011 , which is about 2.75%. Although the calculation of an experimental error was impossible due

Viscosity - centipoises

□ Experimental Results
— Least Squares Curve Fit
○ Titani's Results



Temperature - °C

RESULTS

RUN	VISCOMETER TEMPERATURE (°C)	SUPERHEAT (°C)	A x 10 ⁷	VISCOSITY (cp)
1A	76.4		4.604	0.490*
1B	76.4		4.716	0.490*
2A	76.1		4.896	0.490*
2B	76.1		4.716	0.490*
3-10				
17	82.6	-3.5	4.679	0.472
18	82.7	-0.9	"	0.475
19	82.3	1.7	"	0.471
20	82.3	4.1	"	0.469
21	82.5	6.5	"	0.466
22	82.2	9.1	"	0.465
16	87.7	1.7	"	0.456
15	87.6	3.7	"	0.454
28	88.0	4.2	"	0.441
27	88.5	4.7	"	0.468
14	88.5	8.3	"	0.442
11	88.8	9.5	"	0.441
12	88.1	10.7	"	0.442
13	88.3	14.2	"	0.439
29	89.5	3.5	"	0.436
23	92.9	19.9	"	0.415
24	99.8	26.6	"	0.390
26	105.3	32.5	"	0.374
25	110.1	37.3	"	0.348

The results of runs 2A and 3 through 10 were in error because of warming effects due to an improper unfreezing technique. The value of "A" used in the calculations was an average of the results of 1A, 1B and 2B, which were the three initial runs in which there were no warming effects.

*These viscosity values are taken from Titani's results.

to lack of knowledge of the errors in data taken from other sources, a reasonable assumption is that deviations of less than 3% fall within the experimental error of this study. The experimental error and reliability of Titani's results were not reported.

The results of this study are reported in terms of viscosity values at specific temperatures with the pressure determining the superheat of the liquid. Actually the amount of superheat reported for each run is an average value over the capillary tube. Although the measured temperature may be the same at both ends of the capillary, the amount of superheat will be different because of the pressure differential across the capillary. Throughout the runs, this differential varied from 2 cm Hg to 5 cm Hg, which means that the superheat differential across the capillary ranged from 0.75°C superheat to 2°C superheat.

In the discussion of end effects, the entrance length for development of the parabolic velocity profile was seen to be a function of the Reynolds number, which is also important for verification of laminar flow in the capillary. Calculating the Reynolds number for all of the runs gives a range of values from 86 through 170, which easily fall in the laminar range. (These low figures also verify the logical supposition that flow outside of the capillary is almost stagnant.)

These experimental viscosity values are based on density values obtained by extrapolation into the superheated regime. If there should turn out to be some density anomaly for superheated carbon

tetrachloride, there will also be a secondary anomaly in the experimental viscosity values. A project currently underway to determine densities for superheated carbon tetrachloride should resolve this question.

CONCLUSIONS

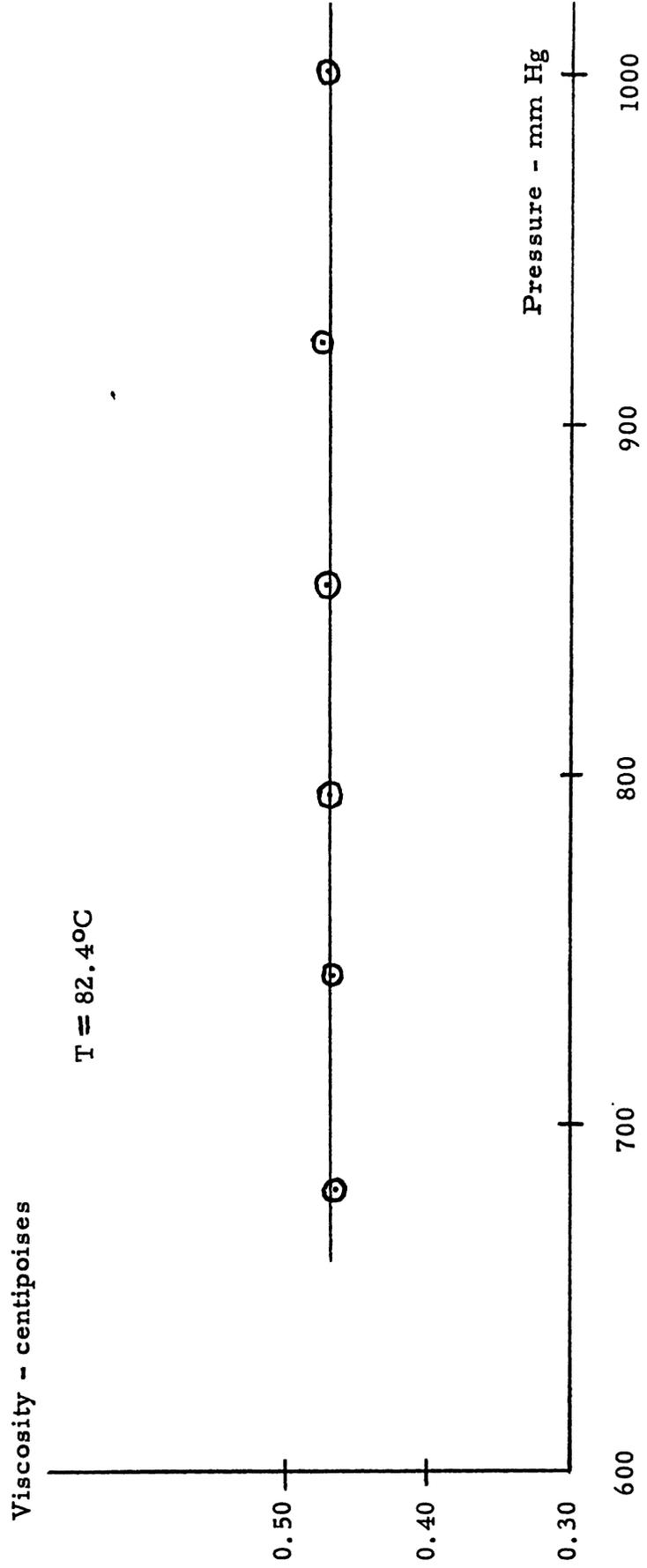
Viscosity data for superheated liquids can be useful in empirical relationships which attempt to predict the viscosity of a liquid mixture from the viscosities of the pure components at the conditions of the mixture. One such equation, given in Reid & Sherwood, p 216 (7), is

$$\mu_{mix} = x_1 \phi_1 \mu_1 + x_2 \phi_2 \mu_2 + 2 (x_1 x_2 \phi_1 \phi_2)^{1/2} \mu_{12}$$

where x is mole fraction, ϕ is volume fraction, and μ_{12} is an empirical constant at each temperature level and may be considered to vary with temperature as a pure viscosity does. The results of this study show that when the required viscosity for a pure liquid falls at superheated conditions, viscosity data obtained in pressurized systems may be used (if the liquid is incompressible). Or if there is some doubt as to how accurate available pressurized data may be (if it is even existent), this study shows that there is a way of experimentally determining the required data.

The data from this experiment were taken in three groups; two sets of runs were taken along isotherms by varying the pressure, and one set was taken along an isobar by varying the temperature. The results of the two isothermal sets of runs show that there appears to be no variation in viscosity with change of pressure (at a constant temperature). This is shown in the graph on the next page where an isothermal set of runs is plotted. There is some slight random scatter, but this is well within the estimated experimental error.

VISCOSITY vs PRESSURE - showing the independence
of viscosity with regard
to pressure



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