ON THE MEASUREMENT OF THE ABSOLUTE VISCOSITY OF NITROGEN AND AIR OVER THE TEMPERATURE RANGE OF 100 TO 400°K AND AT PRESSURES OF 1 TO 150 ATOMSPHERES

by

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree
Master of Engineering

McMaster University
September 1972

MASTER OF ENGINEERING (1972)
(Mechanical Engineering)

McMaster University
Hamilton, Ontario

TITLE: On the Measurement of the Absolute Viscosity of Nitrogen and Air Over the Temperature Range of 100 to 400°K and at Pressures of 1 to 150 Atmospheres

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NUMBER OF PAGES: x, 132

SCOPE AND CONTENT:

A series capillary viscometer has been used to measure the viscosity of nitrogen and air over a temperature range of 100 to 400°K and to pressures of 150 atmospheres.

The low pressure results have been correlated using a modified Sutherland equation of the form:

$$\eta = \frac{C_1 T^{C_2}}{T+C_3}$$

Intermolecular force constants have been computed for nitrogen using the Chapman Enskog collision theory approach.

The viscosity in the dense gas region was correlated using equations of the form

$$\eta - \eta_o = A_1\rho + A_2\rho^2$$

and thus overall equations for viscosity as a function of temperature and density were formulated as

$$\eta = \frac{C_1 T^{C_2}}{T+C_3} + A_1\rho + A_2\rho^2$$

These equations were used to generate tables of smoothed values of viscosity as a function of pressure and temperature.

ACKNOWLEDGEMENTS

The work described in this thesis was supported by the National Research Council of Canada to whom grateful acknowledgement is made.

The author is indebted to Professor Brian Latto under whose guidance he has been privileged to carry out this research, and wishes to thank Mr. David Bonham whose assistance has been invaluable in the area of computer programming, and Dr. Peter Liley* for assistance with reference material.

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NOMENCLATURE

Unless otherwise defined in the text, the symbols used in this work have the following meanings:

D	capillary diameter
g	gravitational constant
h	height
K	Boltzmann constant
L, ℓ	capillary length
m	Hagenback correction factor
n	Couette correction factor
P	pressure
Q	mass flow rate
R	capillary radius, $D/2$
T	absolute temperature, °K
u	fluid flow velocity
V	volume
$\dot{V}$	volume flow rate
z	compressibility factor
α	coefficient of thermal expansion
Δ, δ	difference, differentiation sign
ε	maximum potential energy of attraction
η	coefficient of viscosity
ρ	density
σ	low velocity collision diameter
τ	shear stress, time
ω	weight, reduced density

Subscripts 1 and 2 refer to the upstream and downstream capillaries respectively.

CHAPTER 1

INTRODUCTION

The physical property that characterises the resistance to flow of simple (Newtonian) fluids, be they liquid or gas, is the viscosity. A concept of viscosity is the idea that the internal friction between the molecules of the fluid causes adjacent parts in the fluid to move when either of these parts are caused to move. In actual fact this effect is produced by a change of momentum from one layer in the fluid moving between finite boundaries. The resistance of the fluid to develop a velocity gradient is the essential feature and forms the quantitative assessment of the viscosity.

The viscosity is one of the properties of a fluid termed the "transport properties", the others being the coefficients of diffusion and thermal conductivity, all of which are physically similar in that they involve the transport of some physical property through the fluid.

In a simple fluid, the resisting force produced by the fluid flow is proportional to the velocity gradient and it may be defined by the equation

$$\tau = \eta \frac{du}{dy} \qquad (1.1)$$

where τ is the shearing stress between adjacent parallel layers in a fluid having viscosity η and a velocity gradient of du/dy normal to the axis of flow. This definition first propounded by Newton applies to steady laminar flow.

Accurate experimental viscosity data furnishes a worthwhile contribution to the study of the interrelationship between various transport coefficients of gases and intermolecular models as postulated by different theories. The theory is merely a method of describing certain phenomena which can be refined or replaced by a new one when it is no longer reliable. To justify such changes in a theoretical approach to the problem, experimental proof is important.

In order to improve understanding of molecular interaction in dilute and dense fluids accurate experimental data of the transport coefficients, especially that of viscosity of gases over broad temperature and pressure ranges are required.

Values for viscosity of gaseous substances are also of practical importance in engineering mechanics such as fluid dynamics and heat transfer in fluids, entering directly into Reynolds, Schmidt and Prandtl criteria.

Considering the aspects presented above the main objective of this research is to carry out accurate experimental viscosity measurements of nitrogen and air over a broad pressure and temperature range.

CHAPTER 2

LITERATURE SURVEY

Work relevant to the viscosity of nitrogen and air under dilute gas and dense gas conditions is to be discussed in this section. For a listing of the data presented by other authors the reader is referred to appendix (A3), also Figures (2.1) and (2.2) graphically illustrate the regions which other authors have covered.

LOW PRESSURE VISCOSITY WORK

Vogel [1] in 1914 carried out the first investigation of the viscosity of dilute nitrogen at low temperatures. Two oscillating disc viscometers, essentially of the same design but dimensionally different, were employed to obtain results for some twenty common gases. The viscometers were enclosed in sealed glass vessels, which in turn were located in constant temperature baths. The boiling point of liquid air, 81.6°K and the ice point of water, 273.15°K were the only two temperatures at which the viscosity of nitrogen was measured. Both apparatus were calibrated using dry air at the ice point of water and the measurements evaluated using the Coulomb-Maxwell theory for oscillating discs.

The absolute viscosity of nitrogen given as $\eta_o = 1.678 \times 10^{-4}$

poise at 273.15°K appears to be some 1% above more recent determinations. However the other data point at 81.6°K is in good agreement with the works of Vasilesco [2], Clarke and Smith [3] and this present work, but since no statement of the accuracy of the apparatus has been given its reliability must be considered questionable.

In 1929 Trautz and Baumann [4] reported experimental viscosity data for several dilute gases and gas mixtures. The viscosities of nitrogen and air were obtained using a single capillary transpiration viscometer at fourteen different temperatures ranging from 195 to 583°K. The formula given by Milliken, relating the reference dry air viscosity values to the calibrating temperatures T in °C[$\eta_{AIR,T} = 1823.8\text{-}4 \times 10^{-8}(23\text{-}T)$ poise x 10^7], was used by Trautz and Baumann [4] to calculate their reference viscosities. This formula, which had been used as the standard for most of the work done in North America before 1940, gives the reference air viscosity as about 0.5% lower than that given by Vogel [1], which had been generally accepted as the standard in Europe. Therefore a recalculation of results would be necessary before a comparison could be attempted. Furthermore, Trautz and Baumann [4] apparently made no attempt to estimate the accuracy of these results.

An oscillating disc viscometer, calibrated with air at 22.6°C was used by Sutherland and Maass [5] in 1932 to investigate the viscosity of three common gases, including air, over the temperature range of 80 to 300°K. The use of several heat transfer fluids in the temperature bath permitted a greater number of data points to be obtained than had been possible with the viscometer used by Vogel. In all, eight data points were obtained over the temperature range, with a large gap between 90 and 170°K. A great deal of care was taken to isolate the apparatus from any stray magnetic fields and also to eliminate any static electrical charges. The results are stated to be consistent to within ±.4%.

Johnston and McCloskey [6] in 1940 reported on the viscosities of eight common gases including nitrogen and air over the temperature range of 90 to 300°K. The apparatus employed was one very similar to, and in fact based on, that designed by Sutherland and Maass [5]. By means of a careful selection of heat transfer fluids used in the temperature bath, Johnston and McCloskey [6] were able to obtain data points evenly spaced over the entire reported temperature range. The smoothed results presented are stated to be accurate to within ±.7%, however at the lowest temperatures they are 1.5 to 2.5% higher than the data obtained by all other authors. This would seem to indicate the existence of a systematic error at these temperatures.

In 1945 Vasilesco [2] presented several sets of gas viscosity data covering the broad temperature range of 90 to 1600°K. The viscosity of nitrogen was determined at three points between 90 and 273°K, and that of air at several temperatures in excess of 273°K. The apparatus employed was an absolute Poiseuille type viscometer with platinum capillaries which had first been calibrated with the gas at 273.15°K. In this way the data were presented as a fraction of the ice point viscosity, i.e. η/η_o. Vasilesco [2] estimated that the data were accurate to within ±0.15% with respect to the ice point viscosity. However no attempt to assess the absolute accuracy of the reference ice-point viscosities was reported.

A constant volume transpiration capillary viscometer was employed by Clarke and Smith [3] in 1967 to measure the viscosity of dilute nitrogen in the temperature range of 114 to 374°K. The viscometer was composed of a helical capillary tube mounted between two vessels filled to different starting pressures. The resulting variable pressure drop over the capillary was read several times during each run in order to evaluate a integral-type working equation obtained from the Poiseuille equation. The data were obtained by taking an average of at least five individual determinations at a given temperature, this has the effect of reducing the experimental scatter but does not influence the absolute accuracy which is stated to be better than ±1% at all but the lowest temperatures.

CONCLUDING COMMENTS ON LOW PRESSURE (DILUTE) VISCOSITY DATA FOR NITROGEN AND AIR.

(1) The available low temperature viscosity data is sparse even for one of the more thoroughly investigated gases such as nitrogen.

(2) In the lowest temperature regions, i.e. around 100°K, the discrepancy between the nitrogen data of Clarke and Smith [3] and Johnston and McCloskey [6] reaches a maximum of 3%. A similar condition exists between the only low

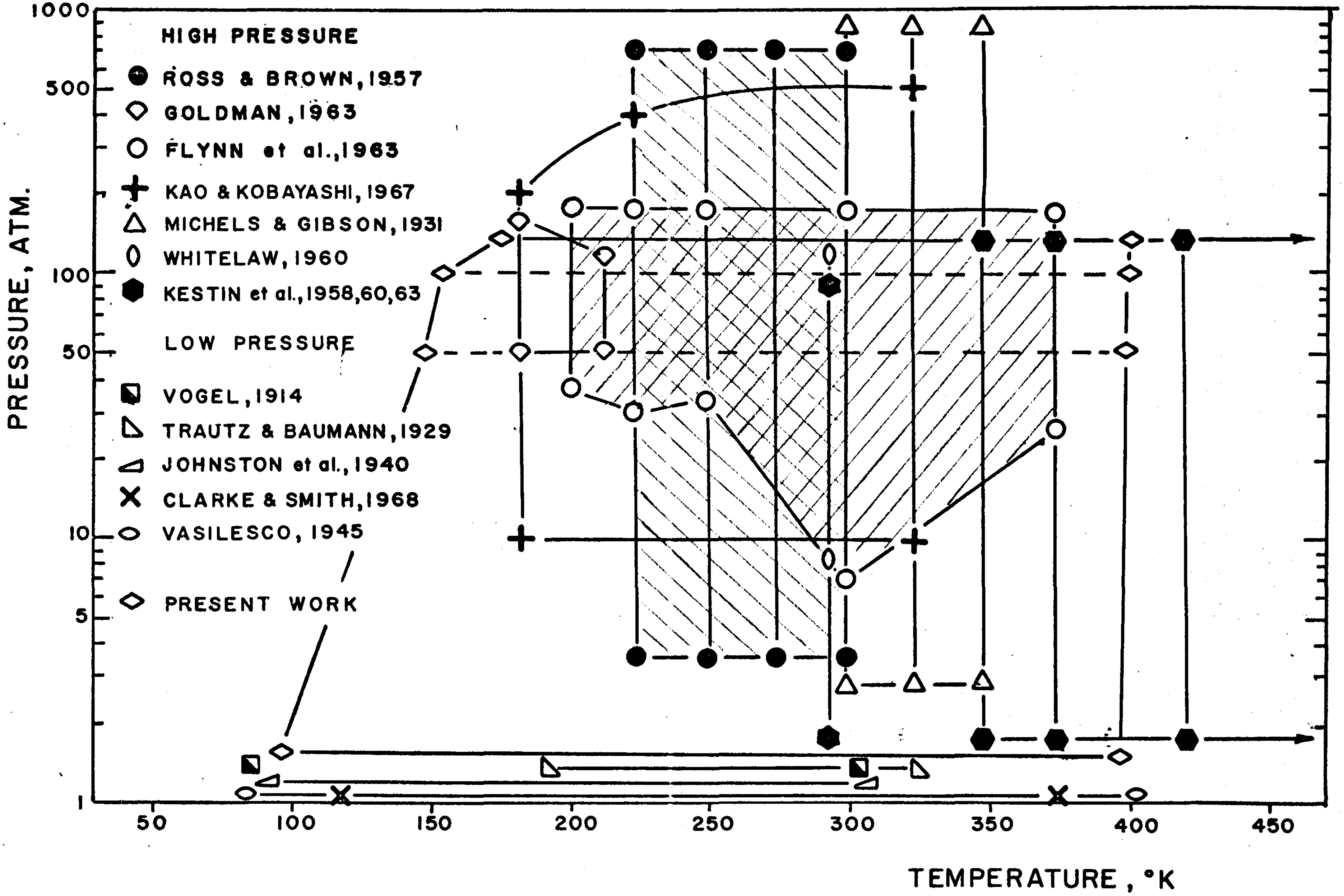


FIGURE 2.1 AVAILABLE NITROGEN VISCOSITY DATA

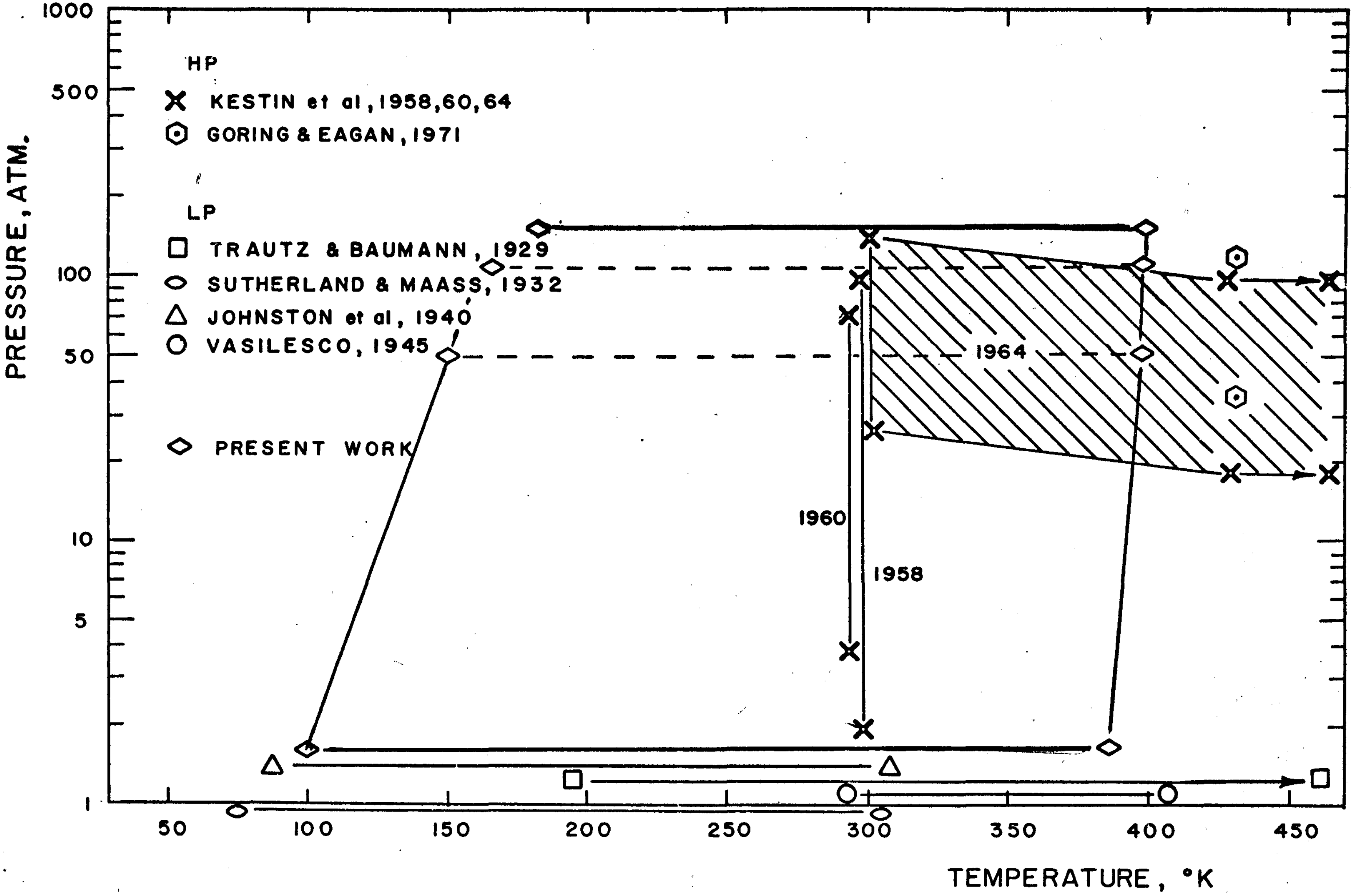


FIGURE 2.2 AVAILABLE AIR VISCOSITY DATA

temperature air data available, that of Sutherland and Maass [5] and Johnston and McCloskey [6].

(3) All dilute low temperature viscosity data for air and all but two determinations for nitrogen have employed oscilating disc viscometers; as recently as 1964 Kestin and Wang [7] stated that the theory of the oscillating disc had not been fully developed and therefore that the results of these earlier determinations were certainly in doubt.

HIGH PRESSURE VISCOSITY WORK

In 1931 Michels and Gibson [8] presented data on the viscosity of nitrogen at pressures of up to 1000 atmospheres and at three isotherms of 298.15, 323.15, and 348.15°k. A non-steady flow capillary viscometer was used, the dense gas being driven through an 80 cm long glass capillary by the pressure produced by a falling column of mercury 30 cm in length. The progress of the dropping mercury was measured using a series of platinum contacts fused into a glass column. The repeatability of the data was reported as ±0.5%, although no actual details of the determination of this accuracy were given, the results appear to be in good agreement with other more recent work.

Ross and Brown [9] in 1957 presented data on the viscosity of nitrogen and two other gases at pressures from 35 to 680 atmospheres and over the temperature range of 223.35 to 298.15°K. The apparatus used for the measurements was a single glass capillary non-steady flow viscometer. The glass capillary, being mounted longitudinally between a pair of metal bellows, was displaced axially causing one bellow to expand and the other to contract, thus forcing gas through the tube. This device was mounted within a thermostated pressure bomb. The tube displacement was measured as a function of time and a careful calibration of the bellows spring constant facilitated the determination of a pressure time relationship and the calculation of the viscosity using the Poiseuille equation. The reported accuracy of the data was ±1% and a comparison with the data obtained by Michels and Gibson [8] shows an average deviation of about 0.5%.

Kestin and Wang [7] in 1958 presented a re-evaluation of viscosity measurements made and presented by Kestin and Pilarczyk [10] in 1954. The work included data on the viscosity of air and nitrogen at 298.15°K and at pressures up to 70 atmospheres. The re-evaluation was made using an improved theory for the oscillating disc viscometer formulated by the authors in 1957. The analysis consisted of the application of a semi-empirical edge correction factor; whereas previous evaluations had considered the disc an infinite flat plate with no edge effects. The correction had the effect of changing the previously published viscosity data by up to 1.7% for air and nitrogen.

The re-evaluated data were plotted as a function of pressure, which in the case of nitrogen exhibits excellent agreement with the work of Michels and Gibson [8]. However there were insufficient air data available to allow any meaningful comparison. The authors state that their correlations for viscosity as a function of pressure at 25°C are accurate to within ±0.6%.

A determination of the viscosity of eleven gases including air and nitrogen, at temperatures of 293.15 and 298.15°K and at pressures of up to 70 atmospheres was published in 1960 by Kestin and Leidenfrost [11]. The apparatus employed an oscillating disc and was claimed to be an absolute viscometer on the basis of a more refined theory developed by Newell [12] in 1959. Although no statement of accuracy was made the data appear to be in excellent agreement with the data of Kestin and Wang [7] and Michels and Gibson [8].

In 1964 Kestin and Whitelaw [13] presented a set of data on the viscosity of dry and humid air, at pressures up to 140 atmospheres and for six isotherms between 298.15 and 523.15°K. An oscillating disc viscometer was employed, which was calibrated with dry air at 293.15°K. The results were stated not to be subject to an uncertainty in excess of ±0.4%. The data were correlated in the form of excess viscosity vs density, the excess viscosity being defined as η excess $= \eta-\eta_o$ where η_o is the viscosity at zero density for a specific temperature; $\eta_o(T)$. The authors' demonstrate that the isotherms below 373.15°K provide an excellent fit to a third order polynomial in density. The higher temperature isotherms, however, appear to produce values of viscosity up to 3.5% higher than previous work by Kestin and Leidenfrost [11] and Kestin and Wang [7]. This trend is not fully understood and cannot be fully accepted. The authors suggest that it may have been caused at higher temperatures by a systematic error in the apparatus.

Whitelaw [14] in 1960 using a transpiration type capillary viscometer, obtained viscosity data on high pressure steam and nitrogen. The nitrogen data covered pressures up to 114 atmospheres and a temperature range of 289.15 to 296.15°K. A detailed error analysis shows the results to be accurate to ±1.1% at the most unfavorable conditions. Although the results show a fairly high degree of experimental scatter they are generally in good agreement with previous authors.

In 1963 Flynn, Hanks, Lemaire and Ross [15] presented viscosity measurements for four common gases, including nitrogen, at pressures of up to 200 atmospheres and over a temperature range of 194.65 to 373.15°K. Previous to this work, there had been no accurate viscosity measurements made at pressures above 1 atmosphere and at temperatures below 273.15°K. The authors used a single capillary steady flow viscometer, the driving pressure being produced by a pair of counter reciprocating pistons driven by a constant speed synchronous motor. A comparison of the work of these authors shows good agreement with that of previous authors; however the stated experimental accuracy of ±0.1% does not appear to be justified or reasonable.

In 1963, Goldman [16] presented a paper covering work carried out exclusively on the viscosity of nitrogen in the dense gas region. Measurements were taken at temperatures of 194.7, 211.9 and 298.2°K and at pressures of up to 120 atmospheres. The apparatus employed was a constant volume single capillary non-steady flow viscometer, the test gas was forced through the capillary by a pressure difference created by the oil in one side of a large U-tube manometer. The viscosity data was found to agree relatively well with the work of Ross and Brown [9] and was correlated using a standard derived formula based on Enskog's theory for dense gases. Although no estimate of the experimental accuracy was reported, the data points had a maximum deviation from the correlation of +5.0 and -1.4%.

The viscosity of nitrogen-helium gas systems was investigated by Kao and Kobayashi [17] in 1967. The results presented for pure nitrogen cover a temperature region from 183.15 to 323.15°K and pressures of up to 500 atmospheres. The apparatus employed was a single capillary steady flow viscometer equipped with a double plunger volumetric pump, which maintained a steady flow throughout a test run. The maximum probable error was reported to be ±0.137%, the overall precision of the results appears to be excellent.

Goring and Eagan [18] in 1971 presented data on the viscosity of air at the temperature of 423.15°K and pressures of 36.75 and 104.79 atmospheres. The viscosity was measured using a single capillary steady flow viscometer, which was callibrated with dry air. The experimental scatter in the determination of the end correction effect was extremely high, as much as 8% at the lowest flow rate. Also a temperature gradient in excess of 20°C was reported along the length of the 20 inch capillary, this is thought to cast dispersions on the accuracy of the data.

In 1966 Lo, Carrol and Stiel [19] presented a paper on the viscosity of air at high pressures, the work consisted of a correlation of work done by twelve previous authors. The excess viscosity $\eta - \eta_o$ was plotted against the parameter P_T/T where P_T is defined as the thermal pressure; $T\{(\partial P/\partial T)_V\}$. The data were correlated using the equation $\eta - \eta_o = 5.76 \times 10^{-5}(P_T/T)^{1.125}$ poise and the results were presented in a tabular form of viscosity as a function of temperature and pressure. The correlation is in agreement with the data at lower pressures to within ±2.5%, however at higher pressures, the deviation is as high as ±10%.

CONCLUDING COMMENTS ON HIGH PRESSURES (DENSE) VISCOSITY DATA FOR NITROGEN AND AIR

(1) High pressure low temperature viscosity data is virtually non-existent even for nitrogen.

(2) No viscosity data for air at densities in excess of 0.17 GM/CC is currently available.

(3) The medium pressure work done by Kestin and Whitelaw [13] exhibits a deviation of +4% from the other medium pressure data available for air.

(4) The present data is the only available data to be produced over the wide pressure and temperature range for either nitrogen or air using a single primary apparatus.

DENSITY

In order to calculate the viscosity from working equation (3.15) it is necessary to have an accurate knowledge of the density of the measured gas at the appropriate thermodynamic state.

In 1971 Coleman and Stewart [20] published a paper on the thermodynamic properties of nitrogen. An equation of state was developed for the temperature range of 70 to 1000°K and at pressures of up to 1000 atmospheres. In correlating the available density data the authors examined the works of twenty nine authors and selected a shortened list of twelve sets of data. The final equation takes the form of pressure, as a function of density and temperature. The inaccuracy of the fit is stated not to exceed ±0.15% at any temperature and pressure.

Vasserman, Kazavchenskii and Rabinovich [21] in 1971 published a book on the thermodynamic properties of air and air components. The equations of state for air and nitrogen were developed in much the same way as that of Coleman and Stewart [20]. The authors present the equation in the form of the compressability factor as a function of reduced temperature and reduced density. Although the equation for nitrogen was not used in this work, a comparison with the calculated densities obtained using the equation of Coleman and Stewart [20] was made and showed excellent agreement over the more dense region, but a deviation of 0.4% in the one atmosphere region. The equation of state for air is claimed to be in agreement with the data to within ±0.2%.

These two equations of state, along with the computer programmes necessary to use them, are presented in more detail in Appendix (A2).

CHAPTER 3

THEORY

The Hagen-Poiseuille equation can be arrived at by considering the forces acting on a fluid moving in a cylindrical pipe, as done by Schlichting [22], where (1) The axis of the tube is the x direction. (2) The tangential and radial components of velocity are zero. (3) The fluid moves under the influence of a pressure gradient which acts in the direction of the x axis. (4) There is no pressure gradient in the radial or tangential directions. Consider a coaxial fluid cylinder of length ℓ and radius y. In order for the condition of equilibrium to be maintained in the x direction the pressure forces $(P_1-P_2)\pi y^2$ acting on the faces of the cylinder must be equal to the shear forces $2\pi y\ell\tau$ acting on the circumferential area, thus:

$$\tau = \frac{P_1-P_2}{\ell} \frac{y}{2} \tag{3.1}$$

In the case of Newtonian fluids

$$\tau = -\eta \, du/dy \tag{3.2}$$

combining equation (3.1) and (3.2)

$$\frac{du}{dy} = -\frac{P_1-P_2}{\eta \, \ell} \frac{y}{2} \tag{3.3}$$

and integrating

$$u(y) = \frac{P_1-P_2}{\eta\ \ell}\,(C-\frac{y^2}{4}) \tag{3.4}$$

The boundary condition of no slip at the wall or u=0 at y=R yields:

$$u(y) = \frac{P_1-P_2}{4\eta\ell}\,(R^2-y^2) \tag{3.5}$$

It can be seen that the velocity profile across the tube is parabolic, and therefore the mean velocity $\bar{u}$ is equal to half the maximum velocity.

$$\bar{u} = \frac{P_1-P_2}{8\eta\ell}\ R^2 \tag{3.6}$$

now introducing the volumetric flow rate $\dot{V} = \pi R^2\bar{u}$ equation (3.6) may be written as:

$$\dot{V} = \frac{\pi R^4}{8\eta\ell}\,(P_1-P_2) \tag{3.7}$$

This was first deduced empirically by G. Hagen in 1839, shortly thereafter by J. Poiseuille and is known as the Hagen-Poiseuille equation of laminar flow through a pipe.

This simple equation is inadequate for accurate work in the above form since the conditions of (a) steady flow, and (b) no slip at the walls, are not totally satisfied.

A correction for (b), the slip at the walls of the tube can be achieved by increasing the fourth power of the radius of the tube by a factor of $\{1+\frac{4\varepsilon}{R}\}$ where R is the tube radius and ε is a function of the mean free path of the molecules of the fluid in the tube.

Knudsen [23] did some experimental work with flow in a tube to find the coefficient of slip. He obtained the formula for the mean free path as

$$L = \frac{8}{3}\,\eta\,\{2/(\pi\rho P)\}^{\frac{1}{2}} = \frac{2.128\eta}{(\rho P)^{\frac{1}{2}}} \qquad (3.8)$$

He carried out a substantial number of experiments with several different fluids on solids and concluded that the slip correction coefficient could best be represented by the equation

$$\epsilon = C\ .\ \frac{8}{3}\,\eta\,\{2/P\rho\pi\}^{\frac{1}{2}} \qquad (3.9)$$

He found empirically that the average value of the constant 'C' was 0.81. The viscosity equation with the slip correction is therefore,

$$\eta = \frac{\pi R^4 \Delta P}{8\ell\dot{V}}\ (1+4\epsilon/R) \qquad (3.10)$$

For simple capillary flow conditions the above equation is still inadequate, since it neglects the acceleration of the flow at the entrance of the tube. The fluid must be accelerated to the parabolic profile it assumes some distance along the tube. It therefore follows that there must be a drop in pressure due to the fact that the fluid will have gained kinetic energy. This, in itself, would not affect the viscosity equation if the velocity could be fully recovered at the exit, however this is not possible and therefore allowances must be made for this loss of head. The pressure drop due to energy losses as the fluid is accelerated into the capillary may be derived from Bernoulli's equation,

$$\Delta P = \tfrac{1}{2}\,\rho\,u^2 = \frac{\rho\dot{V}^2}{2\pi^2R^4} \qquad (3.11)$$

This loss of pressure does not take into account the actual viscous friction in the transition length. In order to allow for this, the end correction is assumed to be of the form, $\frac{m\rho\dot{V}^2}{\pi^2 R^4}$, where 'm' is a constant.

There is a considerable amount of contradictory data and conclusions in the literature concerning the magnitude of the dimensionless correction factor'm'. The values obtained for the constant 'm' vary from 1 to 1.21 from theoretical work. However the experimental work of Flynn et al. [15] stated that m varied from 0.88 to 1.70 and was a function of both temperature and Reynolds number. Unfortunately there are not enough results of sufficient accuracy available to prove or disprove this theory.

The main advantage of the two capillary viscometer is that the end correction term is eliminated. The reader is therefore referred to references [14] and [31] for further information on the value of 'm'.

A further correction, first suggested by Couette [24], is the correction to allow for the viscous drag between the converging and diverging streamlines outside the entrance and exit of a capillary. This correction is usually achieved by increasing the length of the capillary by an amount 'nD', to $(\ell+nD)$, where 'n' is a constant of the order of unity. The value of $n=0.6$, based on recent investigations, is often accepted for a capillary tube having squared ends. With a two capillary viscometer however the Couette correction is largely eliminated and their is no need to discuss it in detail.

The coefficient of thermal expansion of the glass capillaries α is used to correct the capillary dimension. Therefore the final equation for flow through a single capillary is:

$$\eta = \frac{\pi D^4 \ \rho \ g \ \Delta P}{128 \ Q \ (\ell + nD)} \ . \ (1+8\varepsilon/D) \ . \ (1+3\alpha\Delta t) - \frac{mQ}{8\pi\ell(1+\alpha\Delta t)} \qquad (3.12)$$

The present work deals with a viscometer in which two capillaries are in series. The equation for the two capillaries may be expressed as,

$$\begin{aligned} \eta &= \frac{\pi D_1{}^4 \Delta P_1 \rho_1 g (1+8\varepsilon/D_1) \ (1+3\Delta t\alpha)}{128 \ Q(\ell_1 + nD_1)} - \frac{m \ Q}{8\pi\ell_1(1+\Delta t\alpha)} \\ \eta &= \frac{\pi D_2{}^4 \Delta P_2 \rho_1 g (1+8\varepsilon/D_2)(1+3\Delta t\alpha)}{128 \ Q(\ell_2 + nD_2)} - \frac{mQ}{8\pi\ell_2(1+\Delta t\alpha)} \end{aligned} \qquad (3.13)$$

where suffixes 1 and 2 refer to capillaries 1 and 2 respectively.

Treating the equations simultaneously to eliminate m and n we get

$$\eta = \frac{\pi g D_1{}^4 (1+8\varepsilon/D)(1+3\Delta t\alpha)}{128 \ Q(\ell_1 - \ell_2)} \{\rho_1 \Delta P_1 - (\frac{D_2}{D_1})^4 \rho_2 \Delta P_2\} \qquad (3.14)$$

The slip correction was calculated and found to be less than 0.2% at the least dense region, thus the working equation employed was:

$$\eta = \frac{\pi g D_1{}^4 (1+3\alpha\Delta t)}{128 \ Q(\ell_1 - \ell_2)} \{\rho_1 \Delta P_1 - (\frac{D_2}{D_1})^4 \rho_2 \Delta P_2\} \qquad (3.15)$$

CHAPTER 4

DESCRIPTION OF APPARATUS

GENERAL SYSTEM ARRANGEMENT

The apparatus described was built by Hesoun [25] based on an earlier design developed by Latto [26]. The high and low pressure arrangements are described simultaneously as they differ only in minor detail. The general flow diagram and photographs of various components of the viscometer are given in Figures 4.1 to 4.4 which are repeatedly referred to throughout this section.

The test gas was supplied from a gas bottle (A) to the viscometer plenum (E) after passing through a silica-gel dryer (D). A set of high and low pressure regulators (B) and (C) were employed to maintain a constant plenum pressure during the low pressure experiments. The high pressure regulator alone was initially used during high pressure runs. However this proved to produce a slight pressure oscillation caused by the regulator hunting and an arrangement whereby the gas supply bottle after having been filled to slightly above the desired operating pressure and connected directly to the system, was finally employed.

Three copper heat exchange coils were wrapped around the stainless steel high pressure vessel. A heat exchange fluid could be pumped through these coils in order to produce the

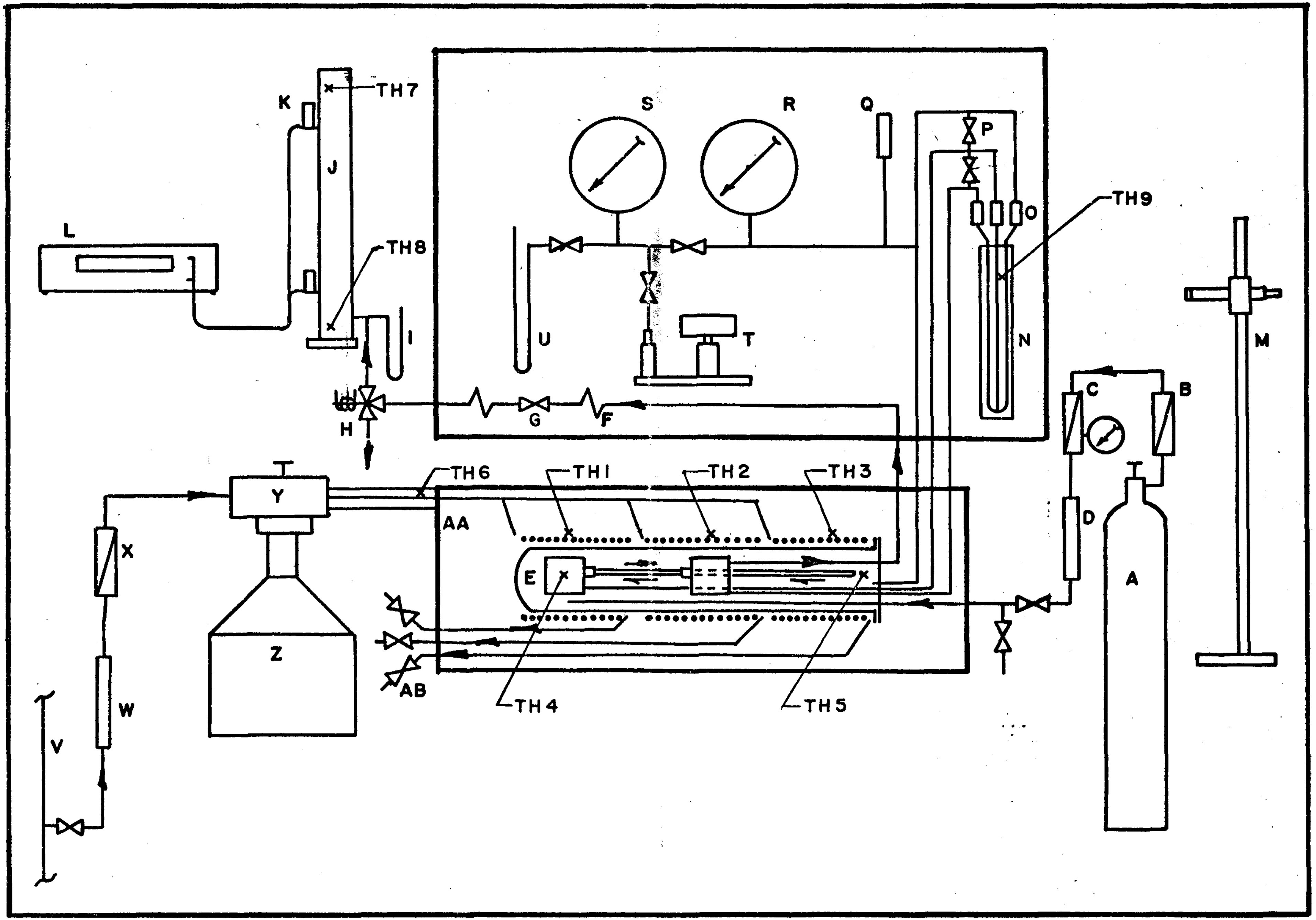


FIGURE 4.1 SCHEMATIC OF VISCOMETER SYSTEM

LEGEND FOR FIGURE 4.1

A	Gas Bottle
B	High Pressure Regulator
C	Low Pressure Regulator
D	Silica-Gel Dryer
E	Viscometer Plenum
F	Heat Exchangers
G	Micro-Metering Valve
H	Solenoid Valve
I	U-Tube Manometer
J	Volumeter
K	Photocell Relays
L	Timer
M	Cathetometer
N	High Pressure Three Limb Manometer
O	Manometer Oil Traps
P	Manometer Release Valves
Q	Safety Valve
R	High Pressure Gauge
S	High Pressure Gauge
T	Dead Weight Tester
U	U-Tube Manometer
V	Air Supply Line
W	Silica Gel Air Dryer
X	Air Pressure Regulator
Y	Coolant Mixing Chamber
Z	Liquid Nitrogen Dewer

AA	Viscometer Insulation Box
AB	Coolant Control Valves
TH1-9	Thermocouples 1 to 9

desired temperature within the viscometer cell. Both the stainless steel vessel and the viscometer cell were maintained at the required temperature.

The test gas enters the upstream (long) capillary directly from the vessel plenum then passes through an intermediate chamber entering the downstream (short) capillary, after this it discharges into the external system. In leaving the temperature controlled pressure vessel the gas flows through two heat exchangers, (F), which restore it to ambient temperature, and a micro-regulating valve (G), then to the low pressure displacement volumeter (J). The gas then exhausts through a three way solenoid valve (H) to atmosphere.

The pressure drops across the capillaries were measured with a high pressure oil-in-glass three limb manometer (N). To protect the plenum during a possible blow out;oil traps (O) were situated in the manometer lines. The absolute pressure of the gas in the plenum was measured using a dead weight tester (T), sensitive to 0.5 psi. For the low pressure experiments a mercury manometer (U) was used. Two high pressure gauges (R) and (S) served as indicators.

The viscometer cell and high pressure vessel were kept at a given temperature by passing an appropriate heat exchange fluid through the heat exchanger coils (AA). Liquid nitrogen was pumped directly into the coils during very low temperature runs or to achieve rapid cooling of the viscometer plenum. A nitrogen rich mixture of precooled air was used to maintain the plenum at moderate to low temperature, and steam was passed through the coils during the high temperature runs. The temperature could be controlled manually by monitoring thermocouples TH1 through TH5 and adjusting the heat exchanger exit valves (AB). After some practice this proved to be a more or less suitable system; however a more convenient control arrangement would have been achieved by the addition of a more sophisticated feed back temperature controller.

A high precision system (not shown in Figure 4.1) was used to measure the thermocouple outputs. this system was composed of "Guildline" Model 9461A Potentiometer together with Model 9460 Photocell Galvanometer Amplifier and Model 9461A Galvanometer.

THE VISCOMETER CELL AND HIGH PRESSURE VESSEL

The viscometer cell and high pressure vessel are shown in detail in figures 4.2 and 4.3. The brass end chambers are connected by ¼" O.D. stainless steel tubes to the outside Swagelok connections. Rubber tubing was used to seal the capillaries to the brass end connectors. This allowed for misalignment within the apparatus as well as considerable variation in the outside diameters of different sets of capillaries. In order to allow for the loss of elasticity of rubber at low temperatures, copper wire was tightly wound around the rubber seals. This simple arrangement proved to be more suitable than some elaborate connectors previously designed and tested.

The use of mixing motors, originally installed in the plenum to help establish a uniform temperature, was discontinued, since they tended to freeze at very low temperatures and were

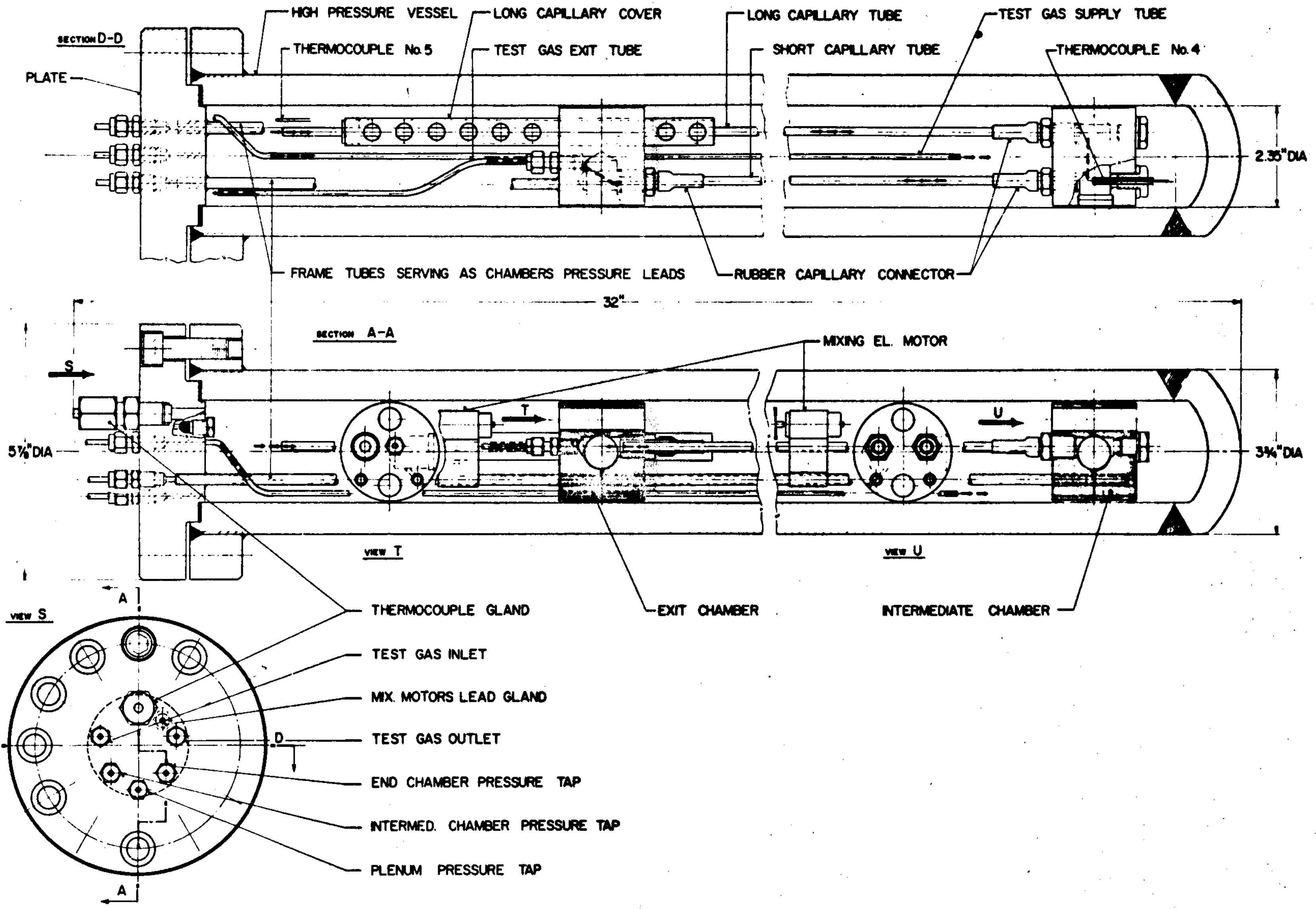
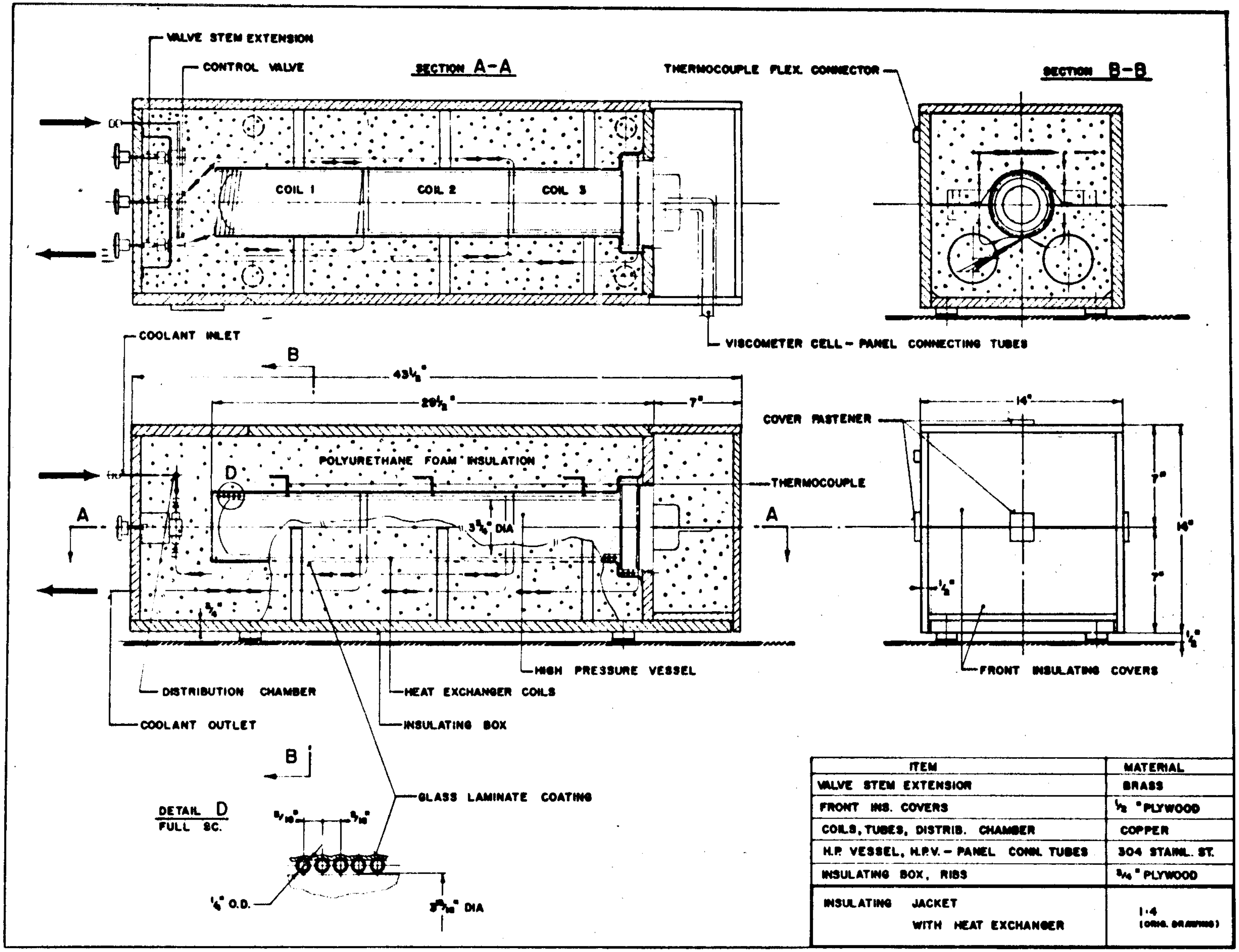


FIGURE 4.2 VISCOMETER CELL AND HIGH PRESSURE VESSEL



ITEM	MATERIAL
VALVE STEM EXTENSION	BRASS
FRONT INS. COVERS	½" PLYWOOD
COILS, TUBES, DISTRIB. CHAMBER	COPPER
H.P. VESSEL, H.P.V. - PANEL CONN. TUBES	304 STAINL. ST.
INSULATING BOX, RIBS	¾" PLYWOOD
INSULATING JACKET WITH HEAT EXCHANGER	1:4 (ORIG. DRAWING)

FIGURE 4.3 INSULATING JACKET WITH HEAT EXCHANGER

found to be unnecessary after a number of initial runs.

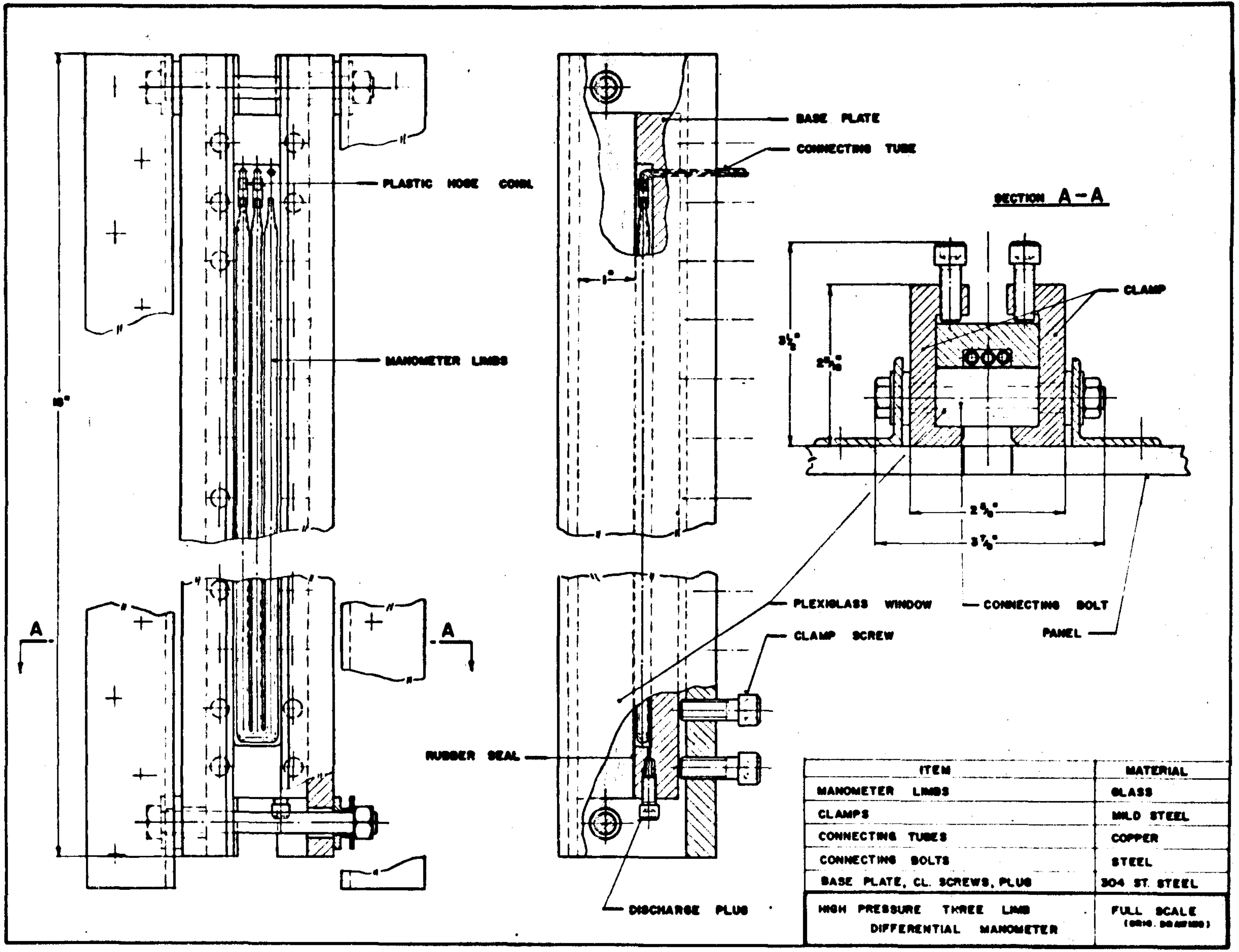
The end chambers were designed with baffles in order to ensure that the flow did not appreciably core. This is important because the elimination of the Hagenbach and Couette corrections depend on similar entrance and exit conditions and therefore zero entrance velocity at both capillaries.

THE HIGH PRESSURE DIFFERENTIAL MANOMETER

A drawing of the high pressure differential manometer is shown in figure 4.4. The oil-in-glass three limb manometer is fitted to a stainless steel back plate and is observed through a thick transparent plexiglass window. The window is sealed to the face of the backplate by means of a rubber gasket and is held in place with thirty-two screws located in two steel clamps. The high precision bore 1/8" I.D. glass tubes of the manometer limbs are about 30 cm long and were filled with manometer oil.

Two of the three limbs were connected, by means of short plastic tubes, to copper lines soldered in the back plate. The third limb was open to the manometer chamber, which was at the working pressure of the viscometer plenum. Both the capillaries and glass manometer tubes are thus not subjected to high differential bursting pressures.

The manometer was read by means of a cathetometer mounted on the floor some two feet away. An additional ½ inch thick plexiglass safety window was installed in front of the manometer window, which fortunately proved to be unnecessary during the entire period of experimentation.



ITEM	MATERIAL
MANOMETER LIMBS	GLASS
CLAMPS	MILD STEEL
CONNECTING TUBES	COPPER
CONNECTING BOLTS	STEEL
BASE PLATE, CL. SCREWS, PLUG	304 ST. STEEL
HIGH PRESSURE THREE LIMB DIFFERENTIAL MANOMETER	FULL SCALE (ORIG. DRAWING)

FIGURE 4.4 HIGH PRESSURE THREE LIMB DIFFERENTIAL MANOMETER

TEMPERATURE CONTROL EQUIPMENT

The heat exchanger equipment consisted of three copper coils wrapped along the length of the high pressure vessel. The vessel and coils were surrounded by polyurethane foam an excellent insulation material. An appropriate heat exchange fluid was passed through these coils.

Over the broad temperature range covered, it was necessary to employ three different heat exchange fluids.

(1) If the desired temperature was very low or if it was desirable to lower the temperature quickly, liquid nitrogen could be forced directly from the nitrogen dewer into the three heat exchange coils.

(2) If the temperature desired was above 150°K and no rapid temperature changes were necessary a low temperature mixture of nitrogen and air was passed through the heat exchange coils. This mixture was attained by bubbling air through the liquid nitrogen dewer. The thermal capacity of gaseous nitrogen is relatively low and this coupled with the large heat capacity of the pressure vessel and viscometer cell resulted in a large thermal inertia, thus facilitating accurate temperature control and stability.

(3) For high temperature runs medium pressure steam was supplied directly to the coils.

The flow rate of heat exchange fluid was controlled by means of valves located in the exit lines of the heat exchange coils. By individually adjusting the quantity of heat exchange fluid passing through each coil it was possible to attain an even temperature distribution along the length of the pressure vessel. Initially the control valves were located on the inlet side of the heat exchangers inside the insulated box, with valve stems and handles extended to the outside, however after some difficulty with valves freezing during low temperature operation they were abandoned and replaced with exit line valves externally mounted.

FLOW MEASUREMENT

Flow measurement was achieved by means of a direct volume displacement method employing a "Brooks" Vol-U-Meter with a total capacity of 1200 cubic centimeters. A frictionless mercury 'O' ring sealed piston was displaced vertically up a precision diameter glass tube. Two photo electric cells, located such that the distance between them represented a precalculated volume, were used to start and stop a "Hewlett Packard" digital timer. On stopping the timer the second photo cell also activated a three way solenoid valve causing the volumeter to exhaust to atmosphere. The photo cells could be set so as to measure nominal volumes of 200, 400 and 800 cubic centimeters.

In order to determine the mass flow rate it is not only necessary to measure the volume flow rate but a knowledge of the gas density is also required. This was achieved by measurement of the temperature and pressure within the volumeter. Thermocouples TH7 and TH8 were located at opposite ends of the volumeter cylinder and a small U-tube oil manometer was connected to the inlet line.

The viscometer cell was connected to the panel instrumentation and to the entrance and exit lines by means of 1/8" OD copper tubing and brass swagelok fittings. When access to the cell was desired to check or replace the capillaries, the insulation box and high pressure vessel was slid back and the viscometer cell supported on wooden blocks.

For a further description of the development and design criteria of the apparatus the reader is referred to reference [25].

CHAPTER 5

EXPERIMENTAL PROCEDURE (PART I)

CAPILLARY CALIBRATION

In the working equation the capillary diameter is raised to the fourth power. This caused an error in measurement of the diameter to be increased by a factor of four in the final viscosity calculation. It is therefore apparent that the diameter of the capillaries must be measured with the utmost precision.

The viscometer was designed to use "Veridia" glass capillaries having high precision bores ranging in diameter from 0.25 to approximately 2 mm. This present work employed capillaries having nominal bores of 0.5 and 0.3 mm for the low and high pressure experiments respectively. The tubes were calibrated using a "mercury thread" method which, in previous works, has proved to be convenient and of sufficient accuracy. The selection of the capillaries and the calibration procedure was conducted as follows.

Initially the capillaries were thoroughly cleaned by soaking in sulphuric acid and rinsing in distilled water and ether. The ellipticity, conicallity and any other irregularities of the tube bores were checked by passing a small mercury pellet along the length of the capillary and observing its variation in length. Graphical illustrations of the bore fluctuation appear in figures 5.1 to 5.4. Two capillaries having the most uniform bores were chosen. The mean diameter of each capillary was then obtained gravimetrically by filling the entire length of the capillary with a thread of mercury. The length and weight of the long thread was measured using a cathetometer equipped with a microscope, and a high precision balance respectively. The measurement of the pellet length was carried out while the capillary was immersed in a glycerine bath, this was done because glycerine which has approximately the same refractive index as glass allows an extremely clear and distortionless view of the mercury pellet. The entire procedure of filling the tube with mercury, measuring and weighing it was carried out several times for each capillary, thus decreasing the influence of random weighing errors.

The capillaries were then cut to the design lengths, accurately faced off, and the lengths measured using the cathetometer. The uniformity of the tube bores was sufficient to consider the mean diameter obtained for the rough uncut tube to be the same as that for the shorter design length.

The theory for both the "short pellet" and "long pellet" calibration methods is straight forward and for further details the reader is referred to reference [26].

VOLUMETER CALIBRATION

The volumeter consisted of a long vertical precision bore glass tube with a light plastic piston, sealed around its

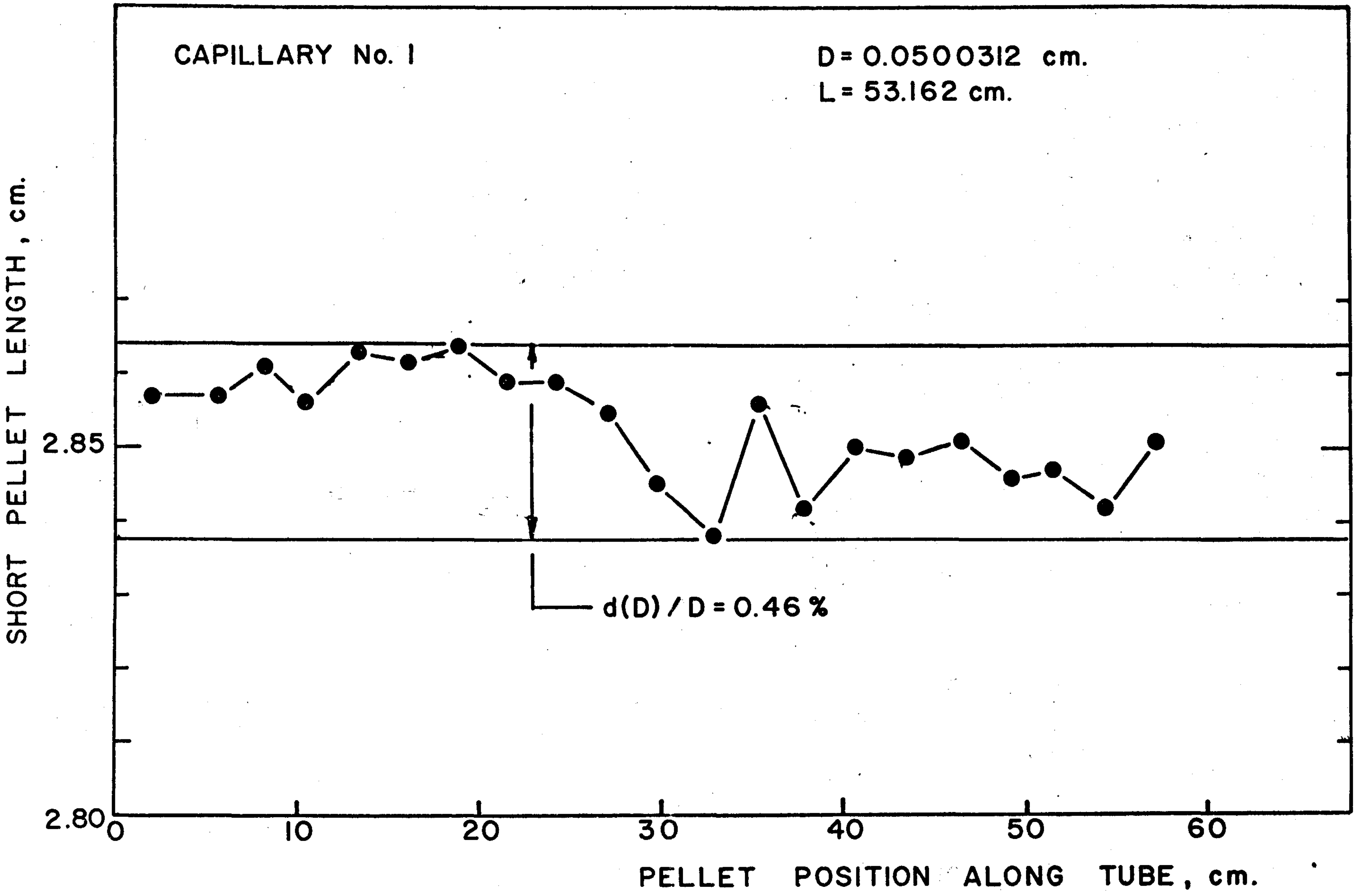


FIGURE 5.1 SMALL MERCURY PELLET CALIBRATION CURVE

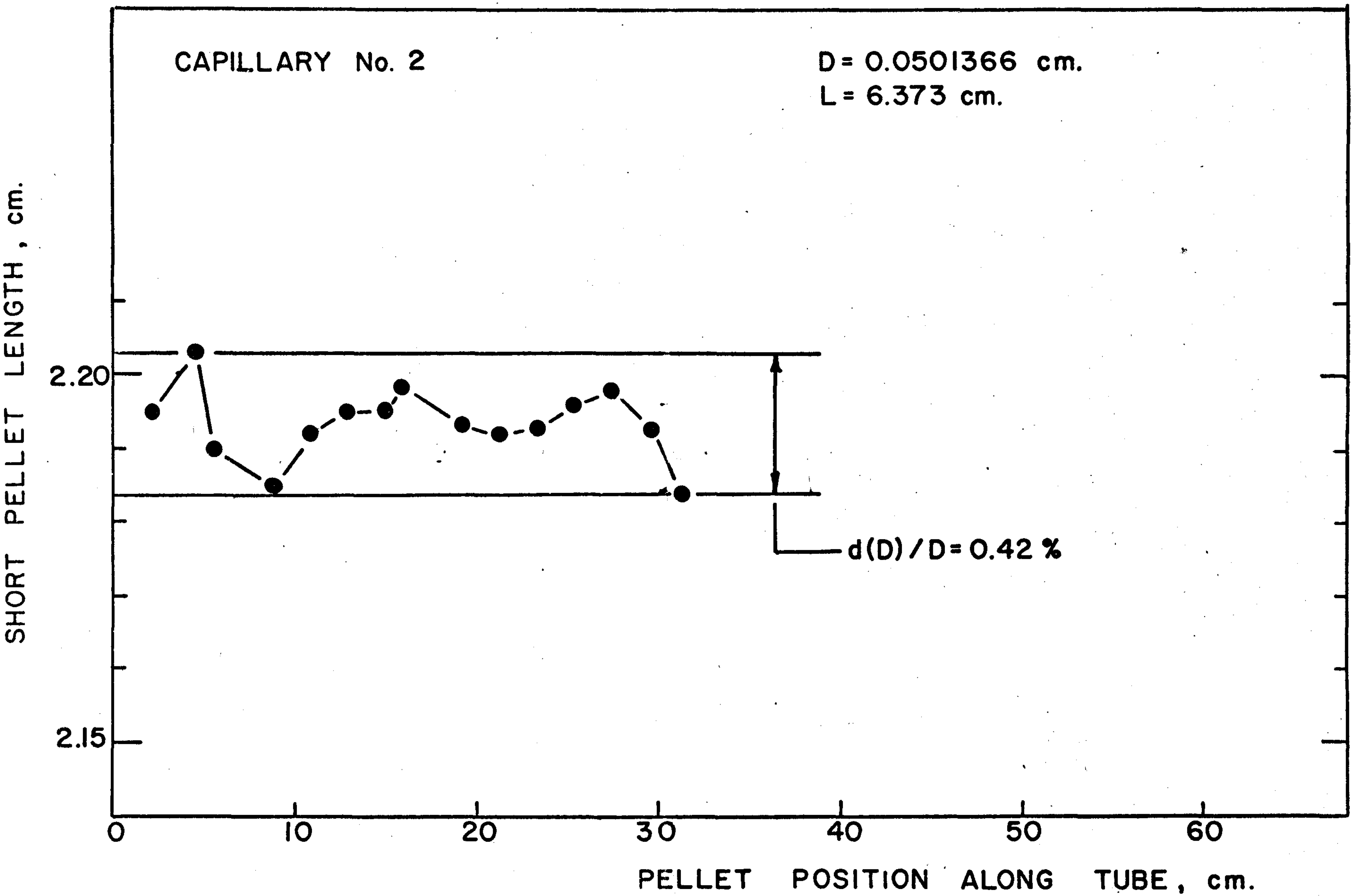


FIGURE 5.2 SMALL MERCURY PELLET CALIBRATION CURVE

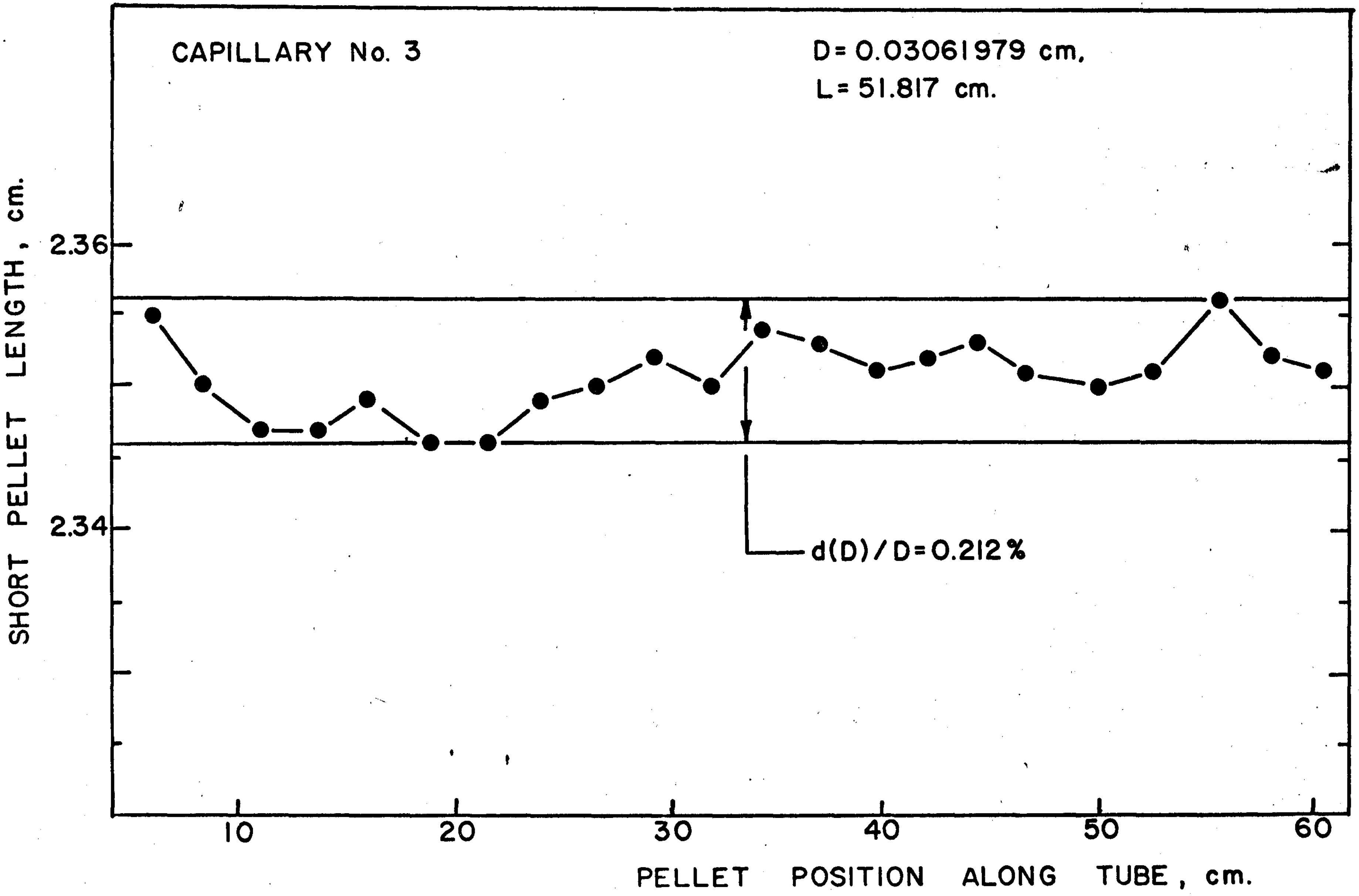


FIGURE 5.3 SMALL MERCURY PELLET CALIBRATION CURVE

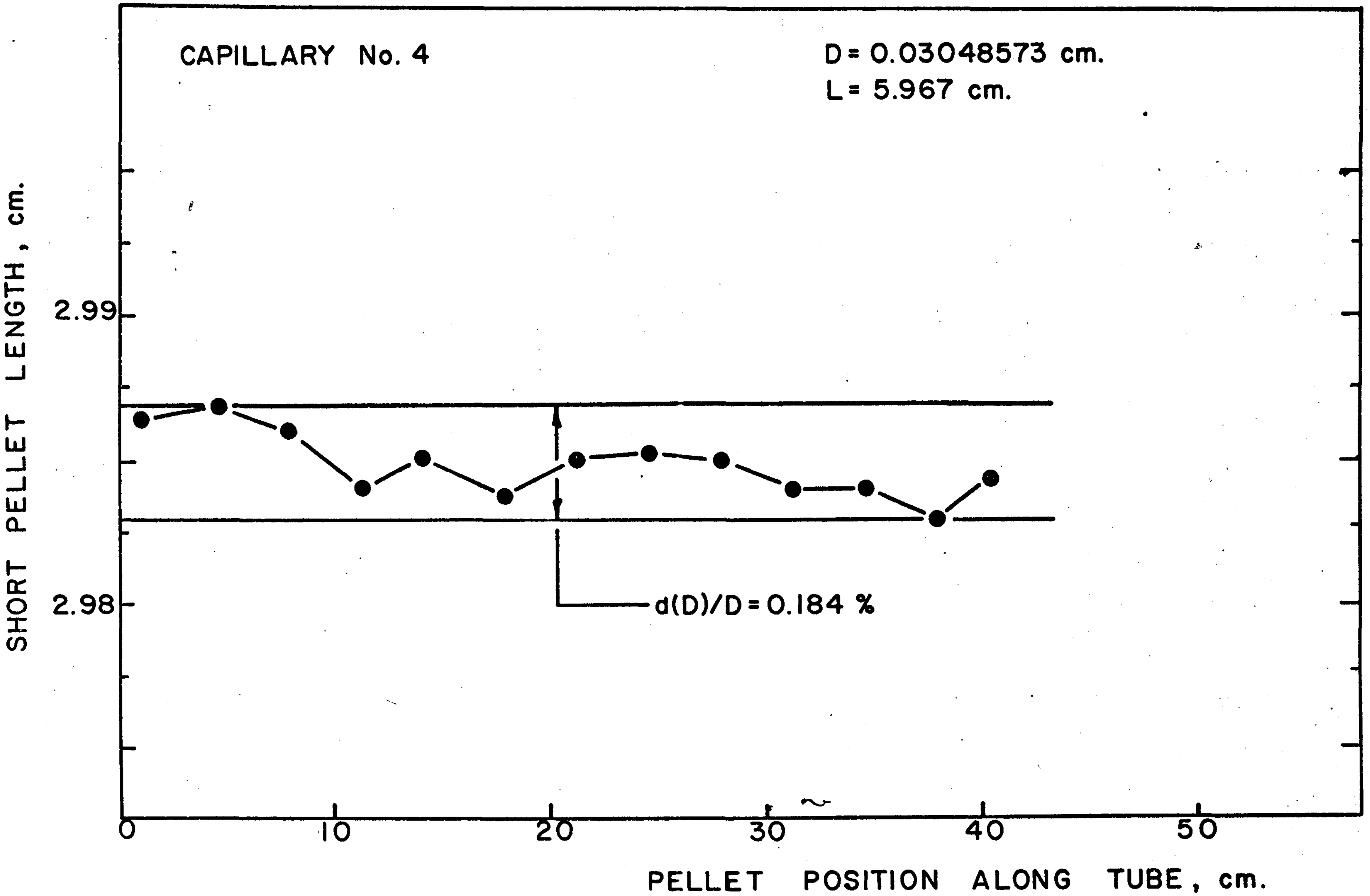


FIGURE 5.4 SMALL MERCURY PELLET CALIBRATION CURVE

diameter with a frictionless mercury '0' ring. The position of the piston within the tube was a measure of the volume of gas in the volumeter. As gas filled the volumeter the piston would move vertically upward, at a certain position the piston would interrupt one of two photo electric cells mounted along the volumeter, thus starting the timer. When the piston had risen a predetermined height it would then interrupt the second photo cell and stop the timer. The distance between these two photo cells was measured using the cathetometer and with the lower photo cell able to be mounted in any one of three positions, nominal timed volumes of 200, 400 and 800 cc were attainable.

The diameter of the volumeter cylinder was measured gravimetrically by filling the tube with distilled water to a measured height and the quantity of water weighed. As in the case of the capillary calibration the procedure was repeated several times to eliminate random errors.

MANOMETER CALIBRATION

The specific gravity of the manometer oil was measured using a standard specific gravity bottle. This proved quite satisfactory for low pressure work, however during high pressure experiments the oil is subjected to considerable pressure which affects its density as well as resulting in gas absorption. In order to obtain a quantitative analysis of the overall effects of gas pressure on the oil the following test was conducted. A given volume of oil was placed in the high pressure manometer and the length of 1/8" ID precision glass tubing it filled was calculated. The apparatus was then pressurized in steps of 20 atmospheres up to 150 atmospheres and the change in length of oil recorded with the cathetometer. The ratio of change in length to original length, $\Delta L/L$, provided a measure of the change in density of the oil as a function of pressure.

The apparatus was further allowed to stand at high pressure for several days in order for gas absorption in the manometer oil to reach equilibrium. The manometer was then quickly decompressed and the manometer oil observed. It was estimated from the volume of disolved gas emitted from the oil that no significant quantity of gas has been absorbed and therefore any change in oil density due to gas absorption could be ignored.

THERMOCOUPLE CALIBRATION

The four most important thermocouples were TH4 and TH5, used to measure the temperatures of the gas entering the two capillaries, and TH7 and TH8 used in the volumeter. Thermocouples 4 and 5 were calibrated at the fixed points of boiling liquid nitrogen, the ice point, and the boiling point of water, also at various other intermediate temperatures against a standard number 705 copper constantan thermocouple which was calibrated by Thermo Electric Ltd., Canada using a reference NBS standard thermocouple APHSS-992/1 and APH 1421, which are claimed to be accurate to ±0.10°C and ±0.06°C respectively. The other two thermocouples, TH7 and TH8 were calibrated over a much smaller temperature range in a similar manner. The calibration curves appear in figure 5.5.

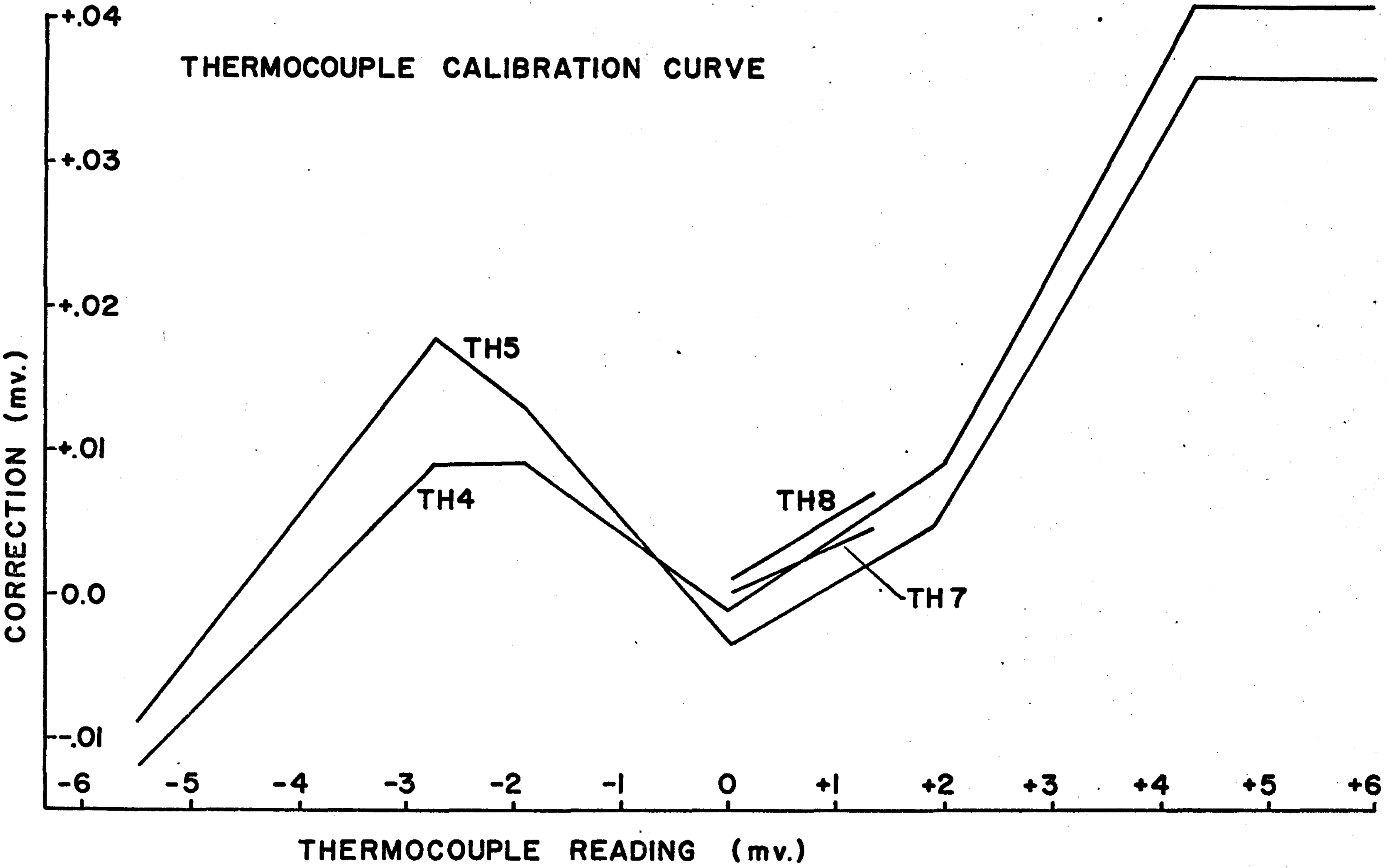


FIGURE 5.5 THERMOCOUPLE CALIBRATION CURVE

The calibration as well as the experimental temperature measurements were done using a high pressure "Guideline Instrument" Potentiometer Type 9160 together with Type 9461A Galvanometer and Type 9460 Photocell Galvanometer Amplifier. This set up is capable of measuring potential difference as small as 10^{-7}volts The systematic error of the temperature measurement is believed to be very close to that of the number 705 copper constantan thermocouple or ±0.1°C.

EXPERIMENTAL PROCEDURE (PART 2)

The viscometer cell was thoroughly cleaned with ether, dried and the capillaries and rubber connecters assembled. The manometer lines to the two end chambers were plugged at the pressure vessel head and the unit was left out of the vessel in order to test the internal connections for leakage.

Since the pressure during normal operation is greater in the plenum than in the capillaries or end chambers, the long capillary was connected to a mercury manometer and the exit line to a vacuum pump. In this way a greater external pressure could be applied to the internal circuit than would actually be encountered during a run.

After the viscometer cell had been leak tested, attention was turned to testing the external circuit and pressure vessel for leakage. The manometer lines were assembled and the pressure vessel bolted into place. The apparatus was then pressurized to 150 atmospheres with nitrogen gas and all external connection tested with leak test fluid. It should also be noted that with the manometer release valves, and the exit valves closed there should be no change in the manometer fluid levels. This however is not the case if there is a leak in one of the manometer lines or in the exit line, and in fact a very slight leak was found to cause a visible pressure differential across the manometer. This provided a mechanism by which the external circuit could be checked after the apparatus had reached the desired operating temperature and proved very useful in preventing small leaks during actual runs.

The viscometer was repeatedly evacuated and flushed with test gas before use. The apparatus was then filled to the desired pressure. During this operation great care had to be exercised to ensure that the manometer release valves were open or the manometer oil would blow out. If a rather potent blow out occurred oil would get into the capillaries and pressure lines. This happened several times during the course of these experiments and necessitated the dismantling and cleaning of the entire apparatus.

The apparatus was brought to the desired operating temperature by pumping liquid nitrogen or steam through the heat exchanger coils while monitoring the four coolant circuit thermocouples and the two internal viscometer cell thermocouples. As soon as the temperature approached the desired value the exit line throttle valve was adjusted to give the desired pressure drop across the capillaries. The heat exchange fluid was then carefully controlled until a suitable temperature equilibrium had been reached, as indicated by the viscometer cell thermocouples. Then the volumeter was switched into the circuit and readings were taken. Firstly all temperature readings, then the atmospheric and the plenum pressures were recorded. The pressure drops across the capillaries were then measured using the cathetometer, and pressure and temperature were measured again then finally the volumeter time was recorded. The measurement of these parameters took approximately 10 to 15 minutes and was done during the time it took for the volumeter to fill. This procedure was repeated several times until a good equilibrium condition had been established and the last set of readings constituted a run.

Considerable care was used to establish the temperature equilibrium simultaneously with an acceptable temperature distribution. The system was usually run for at least four hours before the apparatus was sufficiently stabilized to take any valid experimental readings. Stability of the system during the run is essential if high experimental precision of the viscosity measurements is to be obtained.

CHAPTER 6

ESTIMATION OF ERRORS

It is difficult to make an accurate estimate of the true absolute accuracy of the experimental results. In the foregoing chapter the word accuracy is used to define the relationships of a value to that of a given absolute standard, whereas the precision is defined as the reproducibility of a given value. It is therefore obvious that one cannot have accuracy without precision, but one can have precision without accuracy. In this chapter both the precision and accuracy of the experimental work will be estimated.

There are several factors which limit the accuracy of the results obtained for the viscosity of nitrogen and air using the capillary method. These may be placed in four groups, (1) the reliability of the Hagen-Poiseuille equation, (2) the accuracy of the actual measurements, (3) the experimental corrections and (4) the accuracy of the subsidiary data required, i.e. the properties of the gases used. These four groups will not be discussed separately, but brought together for each assessment.

Commencing with the flow equation for a series capillary viscometer,

$$\eta = \frac{\pi \; g \; (1+3\alpha\Delta T)}{128 \; Q(\ell_1-\ell_2)} \quad (z_1-z_2) \tag{6.1}$$

where

$$z_1 = \Delta P_1 \rho_1 D_1^{\,4}$$

and

$$z_2 = \Delta P_2 \rho_2 D_2^{\,4}$$

and using the "most probable" method to ascertain the overall accuracy and precision of the experimental work i.e. taking the square root of the sum of the squares of the largest errors in each variable.

This method may be represented by the equation

$$d\eta = \sqrt{\sum_{i=1}^{J} \left(\frac{\partial \eta}{\partial x_i} \times dx_i\right)^2} \tag{6.2}$$

Partially differentiating equation (6.1) and putting the results into the form of equation (6.2) we get

$$\frac{d\eta}{\eta} = \sqrt{\begin{aligned} &\left(\frac{dQ}{Q}\right)^2 + \frac{(d\ell_1)^2+(d\ell_2)^2}{(\ell_1-\ell_2)^2} + \\ &\left[\left\{\left(\frac{d\Delta P_1}{\Delta P_1}\right)^2 + \left(\frac{d\rho_1}{\rho_1}\right)^2 + \left(\frac{4dD_1}{D_1}\right)^2\right\} z_1^{\,2} \right. \\ &\left. + \left\{\left(\frac{d\Delta P_2}{\Delta P_2}\right)^2 + \left(\frac{d\rho_2}{\rho_2}\right)^2 + \left(\frac{4dD_2}{D_2}\right)^2\right\} z_2^{\,2}\right] \\ &\times \left(\frac{1}{(z_1-z_2)^2}\right) \end{aligned}} \tag{6.3}$$

This may be illustrated more clearly by the following:

by putting

$$\eta = \frac{\nabla}{(\ell_1 - \ell_2)} \qquad (6.4)$$

Then, applying equation (6.2):

$$d\eta = \sqrt{\left(\frac{d\nabla}{\ell_1 - \ell_2}\right)^2 + \left(\frac{-\nabla d\ell_1}{(\ell_1 - \ell_2)^2}\right)^2 + \left(\frac{\nabla d\ell_2}{(\ell_1 - \ell_2)^2}\right)^2} \qquad (6.5)$$

and therefore,

$$\frac{d\eta}{\eta} = \sqrt{\left(\frac{d\nabla}{\nabla}\right)^2 + \frac{(d\ell_1)^2 + (d\ell_2)^2}{(\ell_1 - \ell_2)^2}} \qquad (6.6)$$

The following assessments of the individual errors will be used in conjunction with equation (6.3) to estimate the overall accuracy and precision.

DISCUSSION OF THE INDIVIDUAL VARIABLES

MASS FLOW RATE

The measurement of the mass flow rate is dependent on three factors, the volume and density of gas collected, and the time taken to collect it. That is

$$Q = V\rho/\tau \qquad (6.7)$$

which leads to

$$\frac{dQ}{Q} = \sqrt{\left(\frac{dv}{v}\right)^2 + \left(\frac{d\rho}{\rho}\right)^2 + \left(\frac{d\tau}{\tau}\right)^2} \qquad (6.8)$$

The density was obtained from an equation of state, which is reported to be accurate to ±0.1%, and a knowledge of the state variables pressure and temperature, which were measured in the volumeter to accuracies of ±0.05 cm Hg and ±0.3°K respectively. This results in an overall density accuracy of ±0.142%.

The volumeter volume was calibrated and is believed to be accurate to ±0.20% and the Hewellet Packard digital timer is exact to five significant digits, or for the worst case ±0.01%.

Thus the overall uncertainty of the mass flow rate Q is ±.245%.

LENGTH OF CAPILLARIES

The long and short capillaries had nominal lengths of 52 and 6 cm respectively, these were measured with the Griffin and George cathetometer to an accuracy of ±0.004 cm. Thus the second term of equation (6.3) contributes to the overall error by ±.012%.

PRESSURE DROPS

The determination of the differential pressures, ΔP_1 and ΔP_2, was dependent on the measurement of the height and density of the oil columns in the high pressure manometer. The error can be expressed by the equation,

$$\frac{d(\Delta P)}{\Delta P}=\sqrt{\left(\frac{dh}{h}\right)^2+\left(\frac{d\rho}{\rho}\right)^2} \qquad (6.9)$$

The apparatus was operated such that the nominal pressure drops across capillaries 1 and 2 were 20 and 3 cm of oil respectively. These were measured to an accuracy of ±0.006 cm using the Griffin and George cathetometer. The density of manometer oil was calibrated using a 'Mettler' balance and standard specific gravity bottle, also corrections for temperature and pressure dependent density changes were assessed and used. It is therefore believed that the corrected value of oil density is accurate to ±0.12%.

From the above observation it was determined that the absolute accuracy of the individual differential pressure measurements was ±.124 and ±.233% for ΔP_1 and ΔP_2 respectively.

TEMPERATURE MEASUREMENT

The temperature inside the viscometer was measured using two copper-constantan thermocouples which had been previously calibrated against two N.B.S. Standard thermocouples certified exact to ±0.1 and ±0.06 centigrade degrees over the temperature ranges of 90 to 270°K and 270 to 400°K respectively. Due to non-isothermal conditions along the length of the viscometer cell, as well as the uncertainty of N.B.S. circular 508 [27] thermocouple tables, the temperature within the apparatus is estimated to be accurate to ±0.3 centigrade degrees. This leads to errors of ±.3% and ±.075% at the temperature extremes of 100 and 400°K respectively.

GAS DENSITIES

The values of the densities of the nitrogen and air were calculated using equations of state given in references [20] and [21] respectively. These equations are stated to be accurate to ±0.1% over the entire density range of this work.

As stated previously the temperatures are believed accurate to ±.3 centigrade degrees. The pressure within the plenum was measured, over the dilute gas range, using a mercury U-tube manometer and at higher pressures with a dead weight tester, these measurements were accurate to ±.01% and .067% respectively. Making the approximate assumption that for a gas $\rho=P/ZRT$, then the equation for the effects of uncertanties in pressure and temperature may be expressed as

$$\frac{d\rho}{\rho} = \sqrt{\left(\frac{dP}{P}\right)^2 + \left(\frac{dT}{T}\right)^2 + \left(\frac{dZ}{Z}\right)^2} \tag{6.10}$$

where dZ/Z represents the uncertainty due to the equation of state used.

Using equation (6.11), table (6.1) has been generated listing the accuracy of gas density as a function of pressure and temperature.

CAPILLARY DIAMETERS

The diameters of the capillaries were measured using a gravimetric method using the equation

$$D = \frac{4}{\pi} \frac{\omega_m}{\rho_m \ell_m} \tag{6.11}$$

where ω_m, ℓ_m and ρ_m represent the weight, length, and density of a long mercury pellet within the capillary.

The equation representing the accuracy of the capillary diameter is therefore:

$$\frac{dD}{D} = \frac{1}{2}\sqrt{\left(\frac{d\omega_m}{\omega_m}\right)^2 + \left(\frac{d\ell_m}{\ell_m}\right)^2 + \left(\frac{d\rho_m}{\rho_m}\right)^2} \qquad (6.12)$$

The density of the mercury was interpolated from Smithsonian tables [28] and believed to be determined accurately to ±0.05%.

The pellet length, nominally 50 centimeters, was measured by means of the Griffin and George cathetometer to an accuracy of ±.002 cm representing a relative error of ±.004%.

A 'Mettler' balance accurate to ±.001 grams was used to measure nominal mercury pellet weights of 0.6 and 1.5 grams for the 0.3 and 0.5 mm diameter capillaries respectively. This results in relative weighting errors of ±.167 and ±.067% respectively.

The overall accuracies of the diameters of the high pressure, 0.3 mm and the low pressure, 0.5 mm capillaries were ±.087 and ±.042% respectively.

OVERALL ACCURACY

From the preceding sections and the use of equation (6.3) the experimental accuracy of viscosity as a function of pressure and temperature has been calculated and is presented in table 6.2.

It should be noted that this represents an assessment of the random error only and does not include systematic error. Errors due to flow instability, oscillation effect, small leaks and so forth are not quantifiable. It is believed however that

TABLE 6.1

ESTIMATED ERROR IN DENSITY AS A FUNCTION OF TEMPERATURE AT HIGH AND LOW PRESSURES

	TEMPERATURE °K				
$\frac{d\rho}{\rho}$ ±%	100	150	200	300	400
Low Pressure	.316	.221	.177	.138	.125
High Pressure		.233	.190	.154	.142

TABLE 6.2

ESTIMATED ERROR IN VISCOSITY AS A FUNCTION OF TEMPERATURE AT HIGH AND LOW PRESSURES

	TEMPERATURE °K				
$\frac{d\eta}{\eta}$ ±%	100	150	200	300	400
Low Pressures	.515	.492	.470	.426	.382
High Pressures		.604	.589	.561	.533

these errors cannot be overlooked in a statement of the reliability of the results, and therefore based on the scatter of the data it is thought that the results have an overall reliability of better than ±1.5% at the highest densities and better than ±1% at densities lower than 0.25 gm/cc.

CHAPTER 7

RESULTS AND DISCUSSION

GENERAL

The absolute viscosity of nitrogen and air were experimentally measured over four nominal isobars of 1, 50, 100 and 150 atmospheres and over the general temperature range of 100 to 400°K. The data are presented in tables 7.1 and 7.2.

LOW PRESSURE NITROGEN

It was decided not to use totally empirical methods of correlation, which often produce a good but physically unjustifiable fit of the experimental data. For example in the case of polynomial correlations, this results in an inability to interpolate outside the experimental temperature range, since an extension of only a few degrees may result in gross errors in the calculated viscosity.

Two semi-theoretical methods were used to correlate the low pressure nitrogen data, these are as follows:

CHAPMAN ENSKOG'S COLLISION THEORY

Presently the rigorous collision theory of gases provides a mathematical expression relating theory with experimental data. The viscosity of a dilute gas may be calculated using the

TABLE 7.1 NITROGEN DATA THIS WORK

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.668247E-04	98.26	1.19	.427865E-02
.829031E-04	122.29	1.20	.340711E-02
.110363E-03	171.31	1.20	.241085E-02
.120244E-03	188.00	1.15	.210612E-02
.125605E-03	196.75	1.21	.211817E-02
.135718E-03	216.04	1.21	.193153E-02
.136312E-03	217.91	1.21	.191525E-02
.139195E-03	224.24	1.20	.183787E-02
.148607E-03	238.32	1.20	.172856E-02
.149252E-03	238.44	1.20	.172734E-02
.157433E-03	255.09	1.21	.163043E-02
.157754E-03	256.24	1.21	.162172E-02
.177536E-03	296.33	1.19	.138073E-02
.177111E-03	296.39	1.19	.137938E-02
.178048E-03	296.98	1.20	.138440E-02
.177706E-03	298.33	1.20	.137512E-02
.178026E-03	298.35	1.20	.137501E-02
.178267E-03	298.37	1.20	.137491E-02
.180011E-03	302.06	1.21	.137451E-02
.179035E-03	302.35	1.21	.137818E-02
.182613E-03	308.96	1.20	.133149E-02
.192183E-03	330.41	1.19	.123462E-02
.193834E-03	334.81	1.19	.121909E-02
.210426E-03	371.64	1.19	.109830E-02
.210318E-03	371.99	1.19	.109712E-02
.210204E-03	374.60	1.18	.108245E-02
.140831E-03	153.65	51.27	.165655E+00
.133528E-03	173.49	50.69	.121829E+00
.134907E-03	185.02	50.98	.109263E+00
.135883E-03	185.43	50.88	.108608E+00
.139287E-03	193.12	49.73	.991328E-01
.137892E-03	193.76	49.73	.986222E-01

TABLE 7.1 CONT'D

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.146383E-03	208.49	51.09	.911674E-01
.146047E-03	208.56	51.02	.909990E-01
.154356E-03	228.27	49.59	.782181E-01
.165000E-03	250.54	51.64	.726212E-01
.169725E-03	260.56	51.62	.692626E-01
.169461E-03	260.96	51.62	.691352E-01
.170217E-03	264.81	49.96	.657387E-01
.184484E-03	293.75	52.46	.613105E-01
.186342E-03	297.83	51.68	.594846E-01
.185409E-03	297.99	51.13	.588143E-01
.205635E-03	351.35	49.33	.474692E-01
.206751E-03	351.48	49.33	.474501E-01
.225143E-03	400.08	50.35	.422699E-01
.224299E-03	400.18	50.38	.422866E-01
.220184E-03	160.92	99.66	.342321E+00
.198990E-03	169.26	100.09	.297177E+00
.183486E-03	186.18	101.90	.239366E+00
.184798E-03	186.32	102.01	.239246E+00
.175230E-03	203.21	100.05	.196894E+00
.175755E-03	203.34	100.12	.196815E+00
.182844E-03	243.44	101.86	.150492E+00
.184718E-03	243.53	101.79	.150313E+00
.198589E-03	296.47	100.24	.114988E+00
.197882E-03	296.49	100.25	.114998E+00
.197978E-03	296.52	100.31	.115046E+00
.198223E-03	296.52	100.36	.115106E+00
.208258E-03	327.62	100.17	.102351E+00
.219864E-03	359.04	100.51	.927603E-01
.220270E-03	359.50	100.51	.926319E-01
.234048E-03	403.25	100.38	.818064E-01
.234022E-03	403.42	100.16	.816023E-01
.254105E-03	177.19	143.40	.367090E+00
.252584E-03	177.44	143.57	.366354E+00
.213406E-03	204.28	144.03	.279651E+00

TABLE 7.1 CONT'D

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.211128E-03	204.83	144.19	.278607E+00
.201786E-03	227.06	144.12	.234340E+00
.203415E-03	262.99	145.75	.191412E+00
.211606E-03	296.17	147.06	.165797E+00
.211507E-03	296.25	147.19	.165876E+00
.210699E-03	296.32	145.32	.163872E+00
.211207E-03	296.35	145.43	.163976E+00
.217809E-03	320.89	144.28	.148059E+00
.217978E-03	321.13	144.21	.147867E+00
.228162E-03	362.13	145.27	.129994E+00
.233984E-03	374.94	141.80	.122393E+00
.243977E-03	403.01	148.59	.118288E+00
.243291E-03	403.07	148.59	.118269E+00

TABLE 7.2 AIR DATA THIS WORK

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.703475E-04	100.78	1.18	.425069E-02
.923310E-04	132.72	1.21	.327473E-02
.110125E-03	162.26	1.22	.267227E-02
.130479E-03	199.79	1.20	.213384E-02
.149331E-03	232.63	1.21	.184949E-02
.156096E-03	243.04	1.22	.177536E-02
.183844E-03	296.71	1.21	.144445E-02
.206417E-03	349.48	1.21	.123104E-02
.227428E-03	396.55	1.22	.108614E-02
.142398E-03	154.92	51.44	.177863E+00
.145556E-03	183.91	52.52	.120836E+00
.164733E-03	241.81	51.61	.791821E-01
.189947E-03	295.70	53.00	.639999E-01
.214843E-03	349.73	54.19	.543680E-01
.234819E-03	398.13	52.90	.462632E-01
.249399E-03	160.53	99.73	.396020E+00
.187178E-03	187.38	101.21	.253913E+00
.185354E-03	241.72	100.88	.158902E+00
.202344E-03	295.27	101.18	.122182E+00
.222240E-03	351.51	99.99	.985478E-01
.240925E-03	398.21	99.68	.857075E-01
.232038E-03	189.38	137.89	.340654E+00
.207530E-03	242.71	140.07	.219279E+00
.215236E-03	295.65	145.21	.172964E+00
.233018E-03	351.55	143.20	.138785E+00
.245432E-03	398.29	139.76	.118092E+00

Chapman Enskog equation for dilute gases

$$\eta = \frac{2.6693 \times 10^{-5}\sqrt{MT}}{\sigma^2\ \Omega_{22}} \tag{7.1}$$

where M is the molecular weight, T the absolute temperature in °K, σ the low velocity collision diameter in Å (the distance at which the intermolecular potential is zero) and Ω_{22} the collision integral calculated from a suitable intermolecular potential function.

Since nitrogen is a non-polar gas, the collision integrals based on the Lennard-Jones [6-12] potential function, which have been found to accurately describe the force interactions of simple non-polar gas molecules, were used for this present work. The Lennard-Jones [6-12] potential assumes that the law of intermolecular potential energy is of the form:

$$E(r) = 4\varepsilon\{(\sigma/r)^{12}-(\sigma/r)^{6}\} \tag{7.2}$$

where the potential energy, E(r), is defined as a function of the distance of separation, r. The distance ε,at which maximum energy of attraction occurs, and σ the collision diameter, are molecular constants.

The results of this theory, however, are applicable only to dilute gases, which can be defined as those whose properties are completely determined from the mechanism of binary collisions between gas molecules.

The collision integrals Ω_{22} which were used in this work were obtained from Liley's work [29] which tabulates Ω_{22} as a function of the reduced temperature, $T^* = T/(\varepsilon/K)$, where K is the Boltzman constant.

Over the entire temperature range covered, i.e. 100 to 400°K the optimum molecular parameters were found to be: σ=3.630 Å and ε/K = 101.14°K. These produced a standard deviation from the 26 dilute nitrogen data points of 0.807% and a maximum deviation of -1.65%, which is considerably higher than the expected experimental precision. However the experimental data were also fitted over the narrower temperature range of 170 to 400°K and parameters of σ = 3.567 Å and ε/K = 114.08°K produced a standard and maximum deviation of 0.405 and -0.956% respectively which is within the experimental precision expected, and is in close agreement with most existing data.

Unfortunately, there appears to be no unique value for the length parameter σ and the energy parameter ε/K which will result in a perfect fit of experimental data over a wide temperature range. This may be due to the inadequacy of the molecular model or the sensitivity of this approach to the experimental accuracy. However it is more likely to be due to the former reason. The above correlations were not used any further in this work.

MODIFIED SUTHERLAND EQUATION

The Sutherland viscosity equation is based on a more primitive model of molecular interaction than the Chapman-Enskog equation, and is of the form:

$$\eta = \frac{C_1 T^{C_2}}{(T+C_3)} \qquad (7.3)$$

The constant C_2 is equal to 1.5 in the classical Sutherland equation, however allowing C_2 to be a variable in these present correlations, improved the closeness of fit considerably.

The modified Sutherland equation was used to correlate both the nitrogen and air low pressure data. Several high order polynomials were also tried but did not produce significantly better results.

The optimum fit for the 26 low pressure nitrogen data points was obtained with the following

$$\eta = \frac{5.58114 \times 10^{-4} \times T^{1.04322}}{T + 900.670} \quad \text{POISE} \qquad (7.4)$$

which results in a standard deviation of 0.51% and a maximum deviation of -0.95%. Figure (7.1) gives a plot of viscosity vs temperature for this current nitrogen data, showing the fitted curve generated using equation (7.4). The high pressure data points are represented on this graph by symbols of different shape. A deviation plot of viscosity against temperature for all the available low pressure nitrogen data is given in figure (7.2). The deviation plot shows that the results of this work are in good agreement with those of previous authors above the temperature of 220°K, but at the lower temperature of 200°K the viscosity equation appear to be some 1 to 2% lower than the data of Clarke and Smith [3], Johnston and McCloskey [6], Vasilesco [2] and Trautz and Bauman [4], at the lowest temperature of 100°K however all the data is in good agreement except that of Johnston and McCloskey [6]

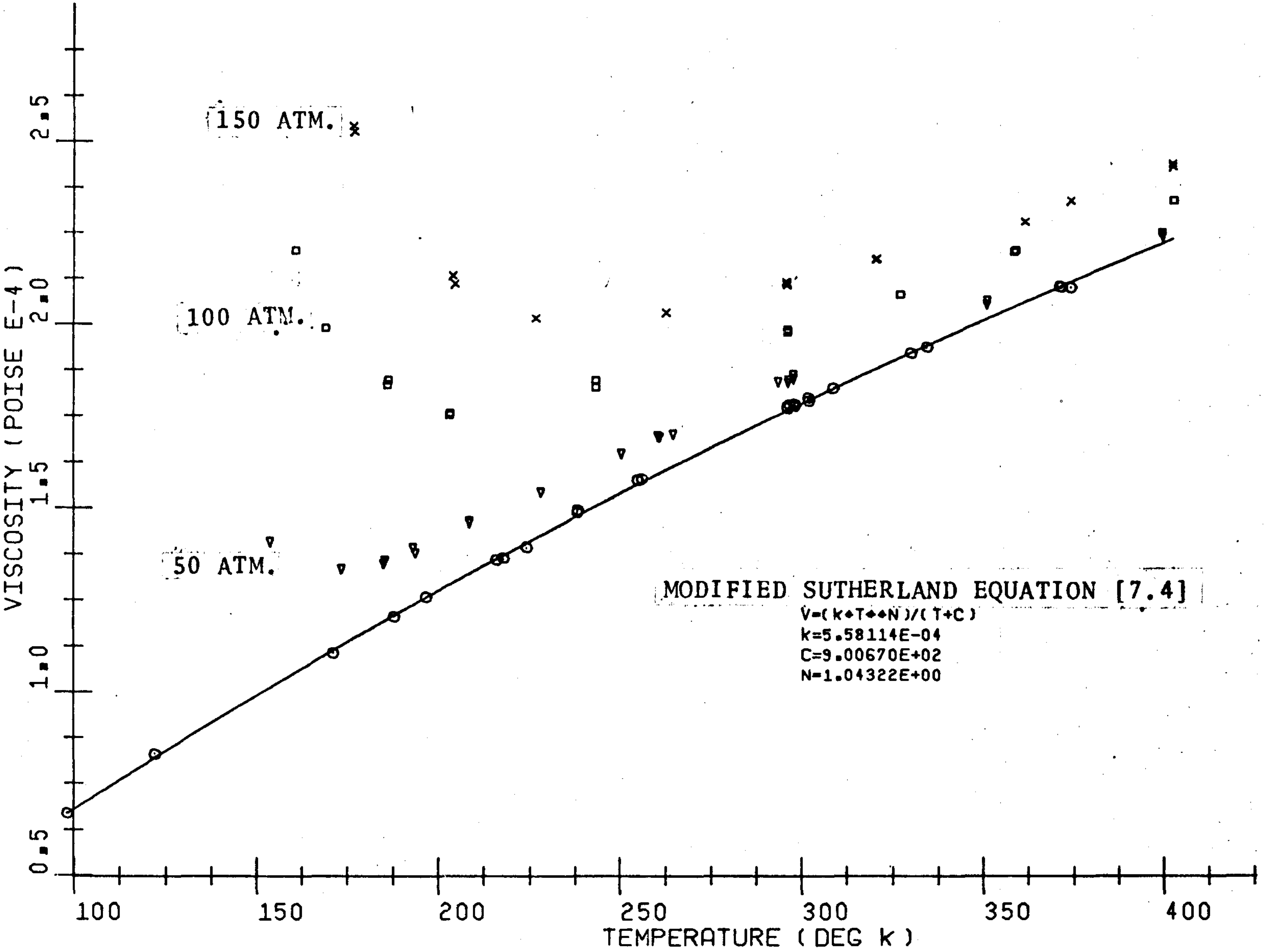


FIGURE 7.1 VISCOSITY OF NITROGEN VS TEMPERATURE

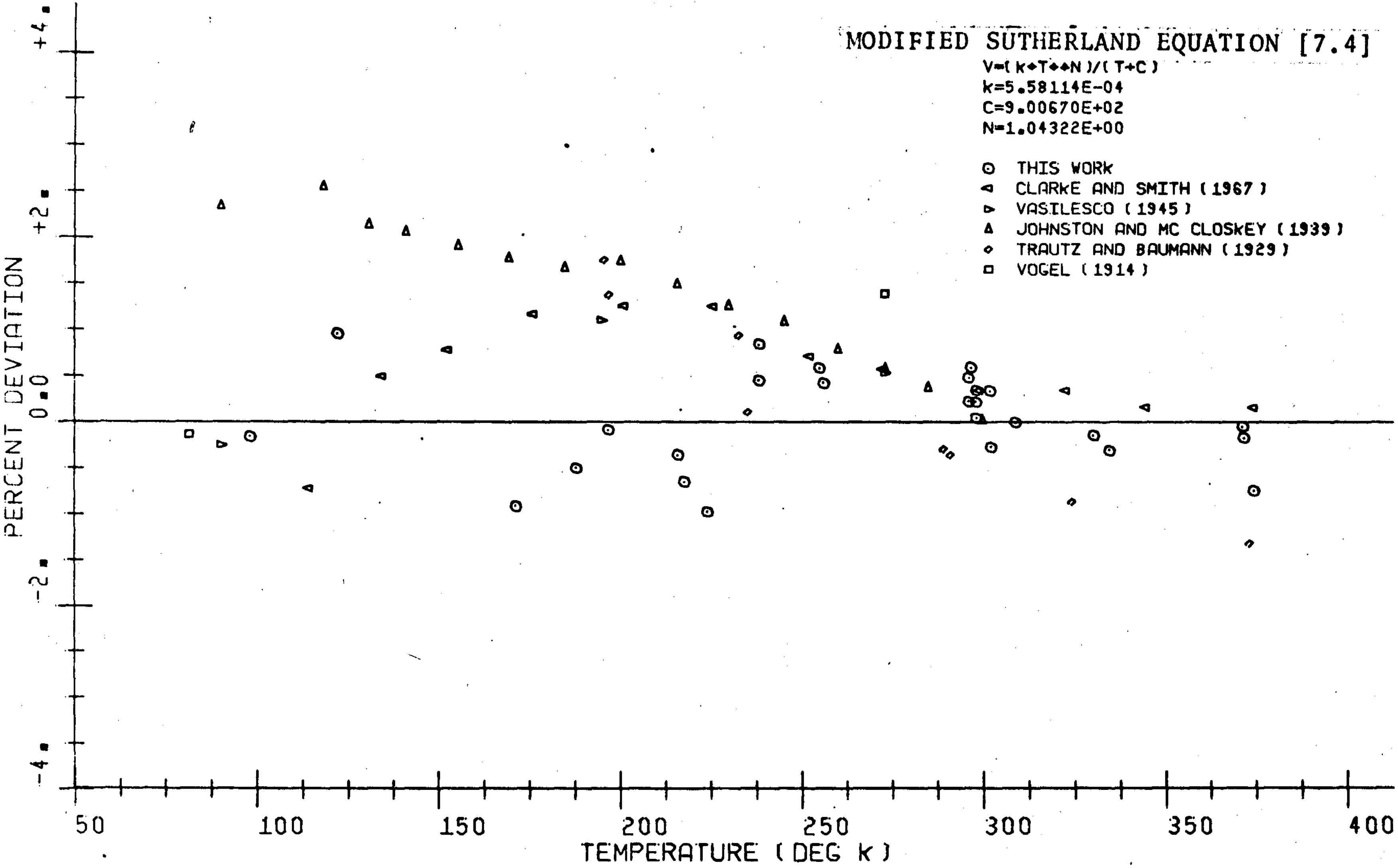


FIGURE 7.2 LOW PRESSURE NITROGEN DEVIATION PLOT

which is some 2% higher. There appears to be some systematic error in the low temperature work of Johnston and McCloskey [6], as stated in the literature survey.

HIGH PRESSURE NITROGEN

A general correlation of the available medium and high pressure nitrogen data including data given in references [7] to [17] is presented in figure (7.3) which shows a graph of excess viscosity $(\eta-\eta_o)$ against the density ρ. The data were correlated using the following equation:

$$\eta-\eta_o = 9.84255 \times 10^{-5}\,\rho + 6.98169 \times 10^{-4}\rho^2 \text{ POISE} \quad (7.5)$$

which is based on equation (7.4) for η_o, the dilute viscosity of nitrogen. Thus a general equation for the viscosity of nitrogen as a function of temperature and density can be written in the form:

$$\eta = \frac{5.5811 \times 10^{-4} T^{1.0432}}{T + 900.67} + 9.8426 \times 10^{-5}\rho + 6.9817 \times 10^{-4}\rho^2 \text{POISE} \quad (7.6)$$

A deviation plot of viscosity $(\eta-\eta_{CAL})/\eta$, against density ρ, where η_{CAL} is the viscosity calculated from equation (7.6), is presented in figure (7.4). This plot indicates that there is a maximum scatter of the overall data from the fitted equation (7.6) of ±4%. However the standard deviation is only 1.2%.

There do not appear to be any discernable trends in the other data compared to the present data, or any apparent systematic discrepencies. The present data being the only data that has covered the entire density range shown with a single apparatus.

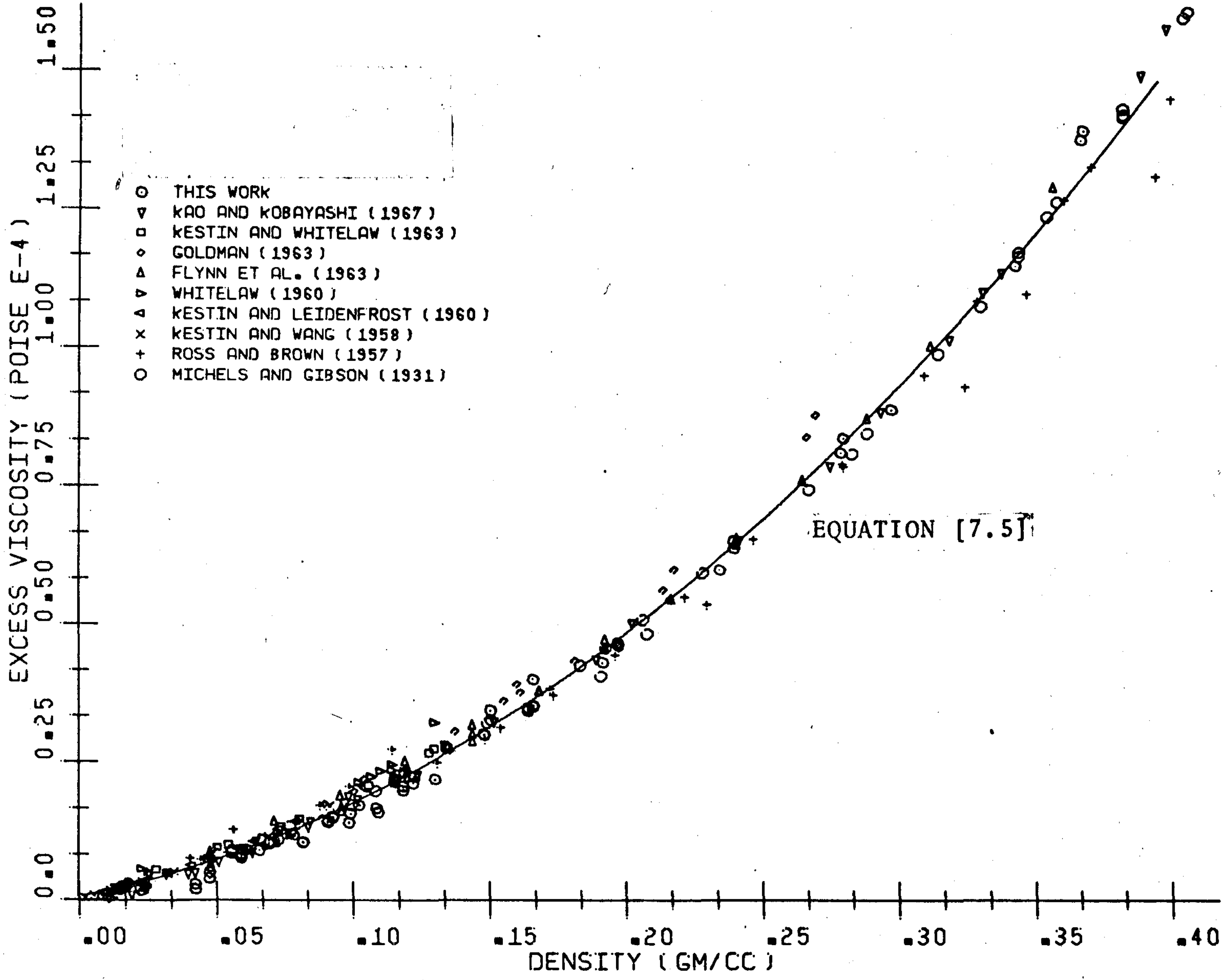


FIGURE 7.3 EXCESS VISCOSITY OF NITROGEN VS DENSITY

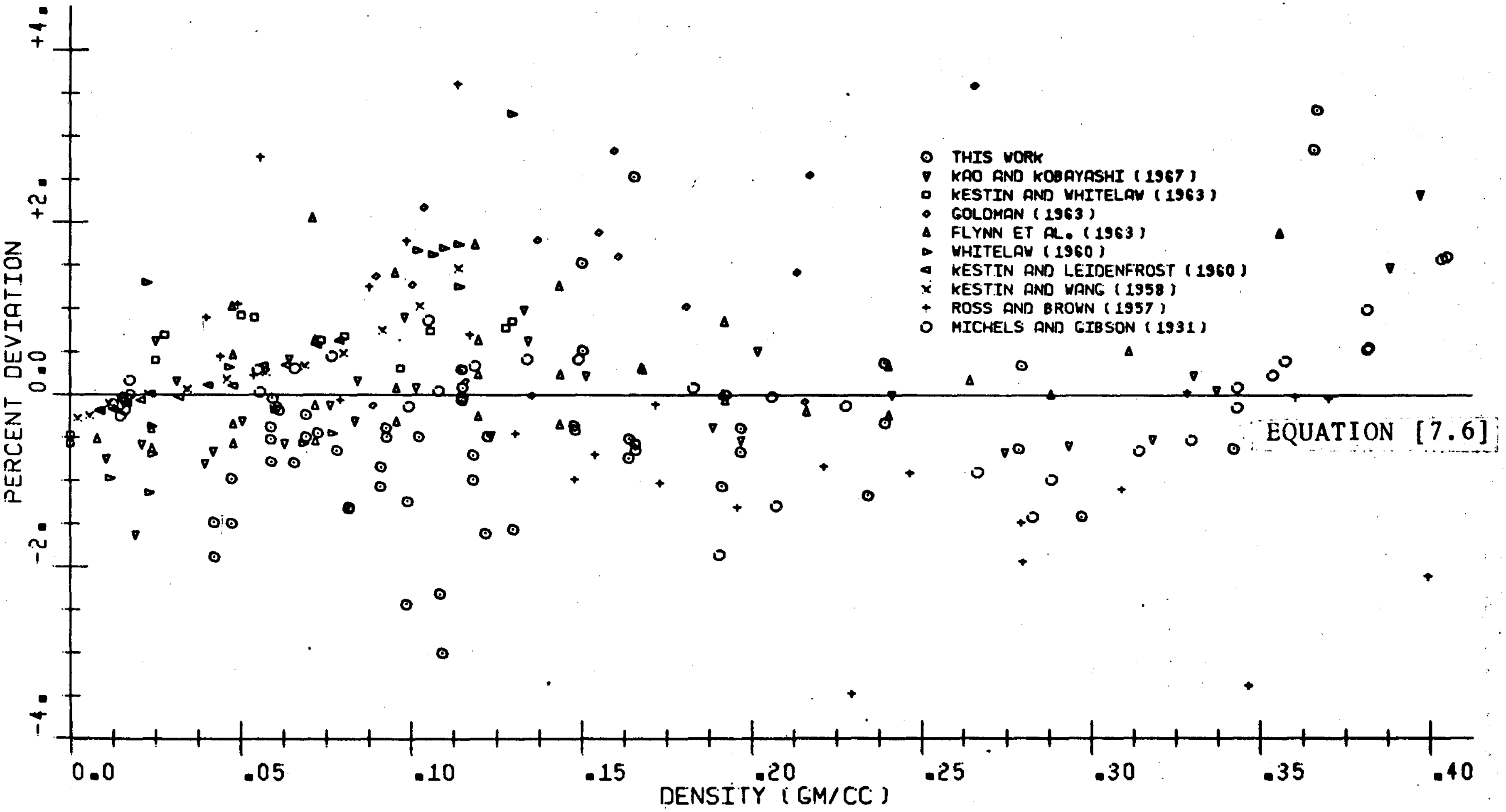


FIGURE 7.4 HIGH PRESSURE NITROGEN DEVIATION PLOT

Graphical illustrations of nitrogen density and viscosity as functions of pressure and temperature using the equation of state from reference [20] and equation (7.6) are presented in figures (7.5) and (7.6) respectively. Also equation (7.6) was used to produce table (7.3), nitrogen viscosity as a function of pressure and temperature.

LOW PRESSURE AIR

The modified Sutherland equation was the only correlating equation used for the air data presented in this work. The optimum fit to the 9 low pressure air data points was produced using the equation:

$$\eta = \frac{3.84475 \times 10^{-4} T^{1.08224}}{T + 700.795} \quad \text{POISE} \qquad (7.7)$$

which has a standard deviation of 0.57% and a maximum deviation of 1.0% from the data. Figures (7.7) and (7.8) show respectively plots of viscosity against temperature for this work, with the low pressure curve drawn using correlating equation (7.7), and a deviation plot of all the available low pressure air data.

The deviation plot shows reasonably good agreement between this work and that of previous authors. However, as in the case of nitrogen, the work of Johnston and McCloskey [6] appears to be some 1 to 2% high in the lower temperature region. The only other data available at the lowest temperature was that of Sutherland and Maas [5] which is some 1 to 1.5% lower than the correlating equation.

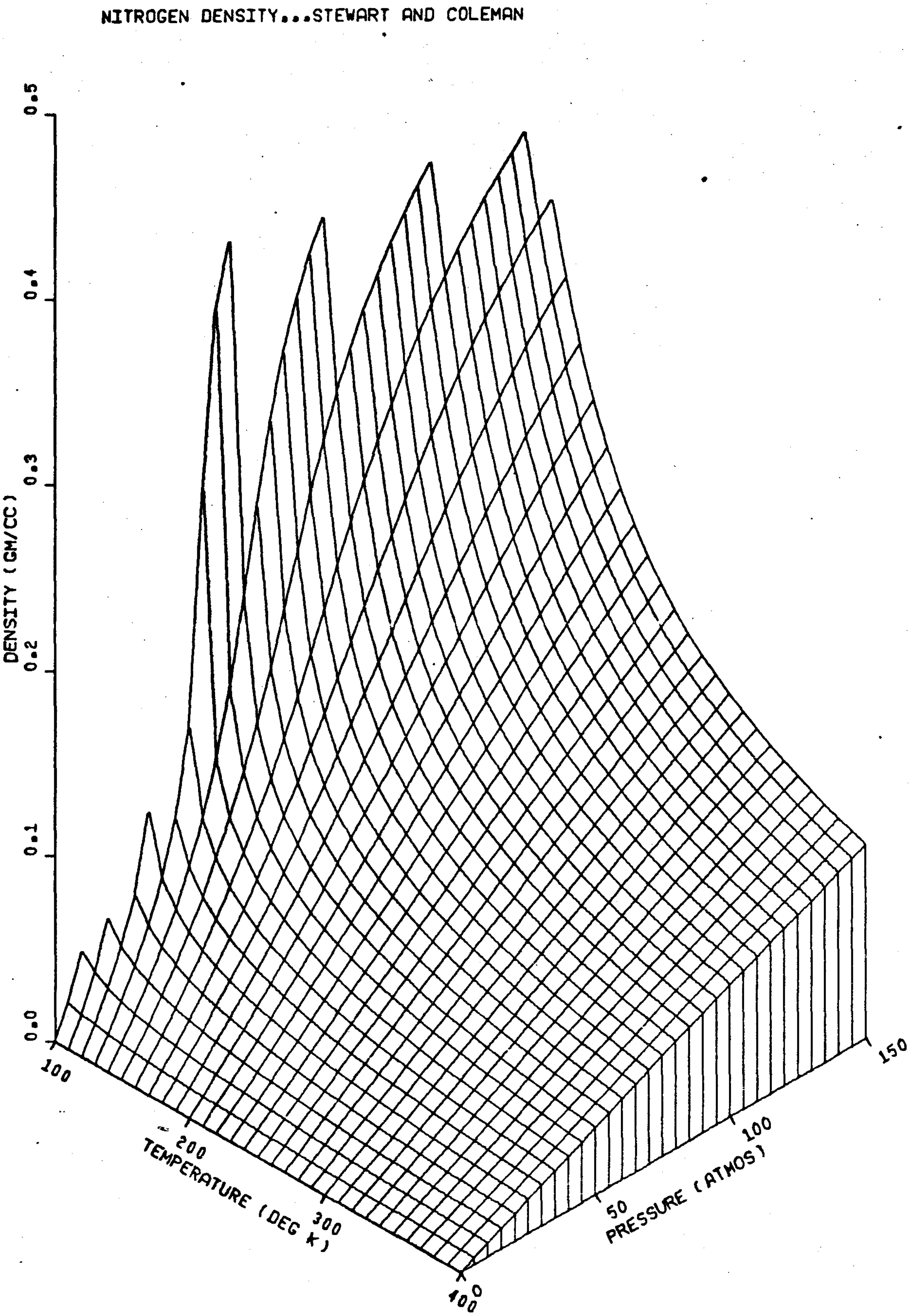


FIGURE 7.5 THE DENSITY OF NITROGEN

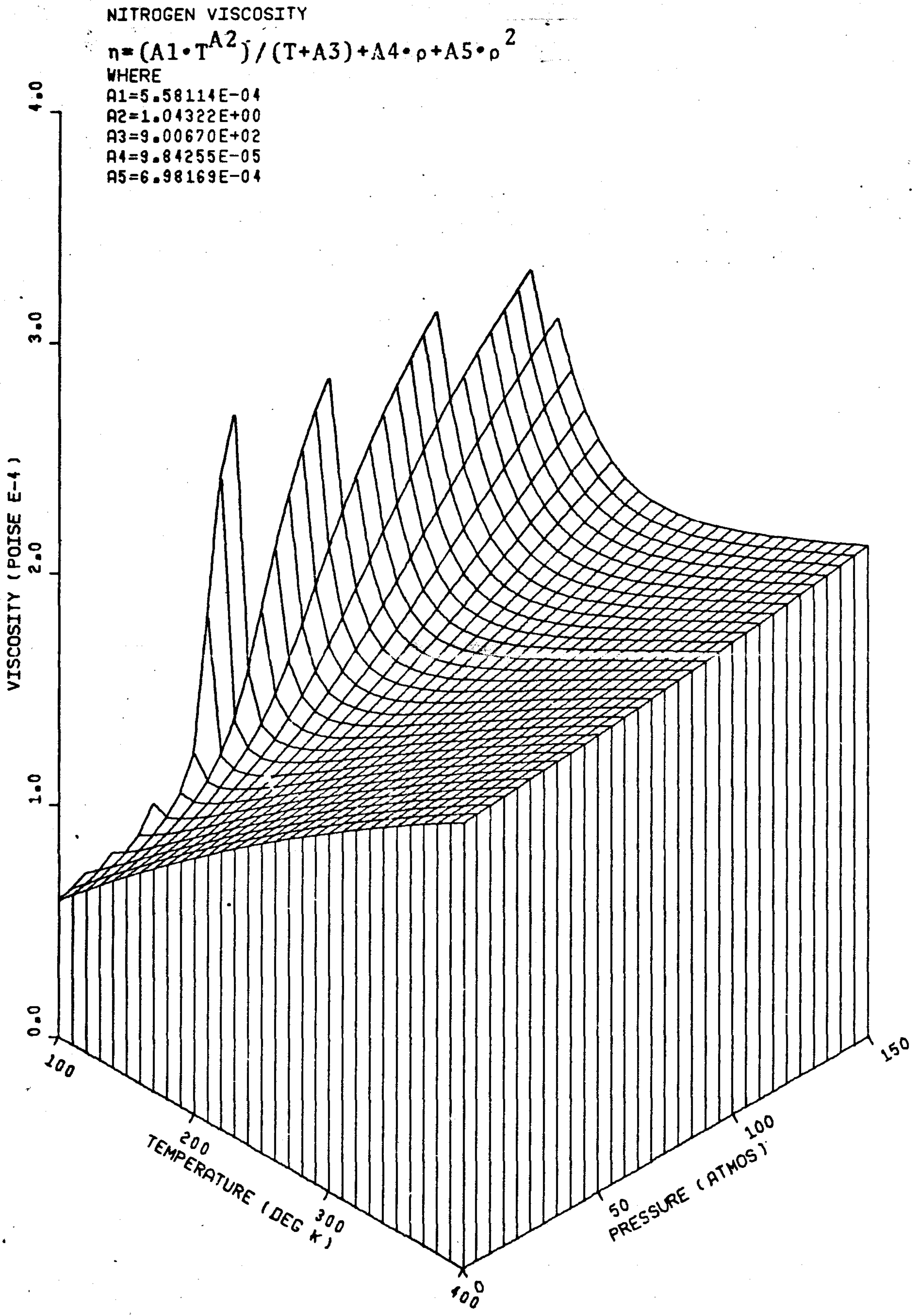


FIGURE 7.6 THE VISCOSITY OF NITROGEN

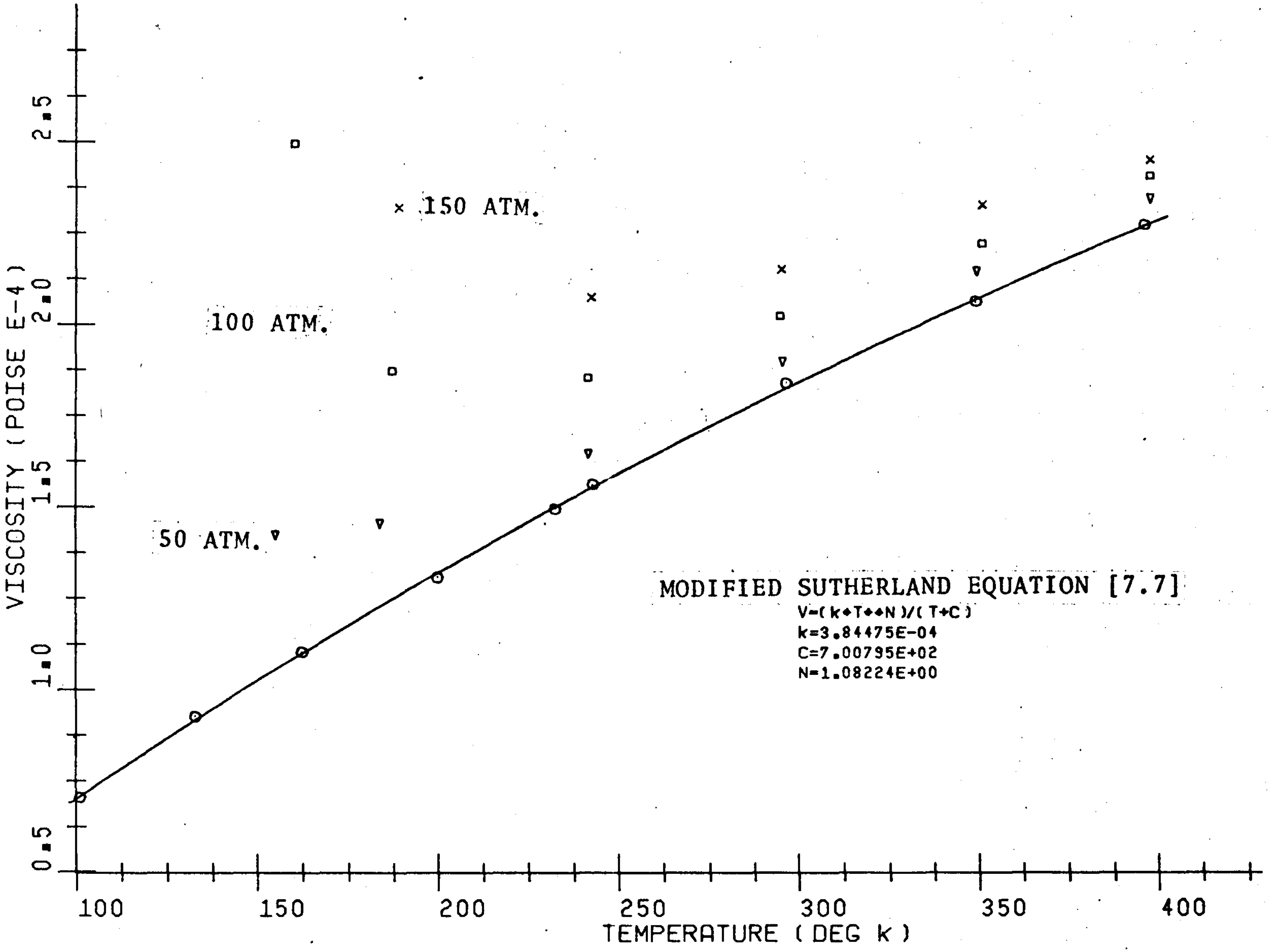


FIGURE 7.7 VISCOSITY OF AIR VS TEMPERATURE

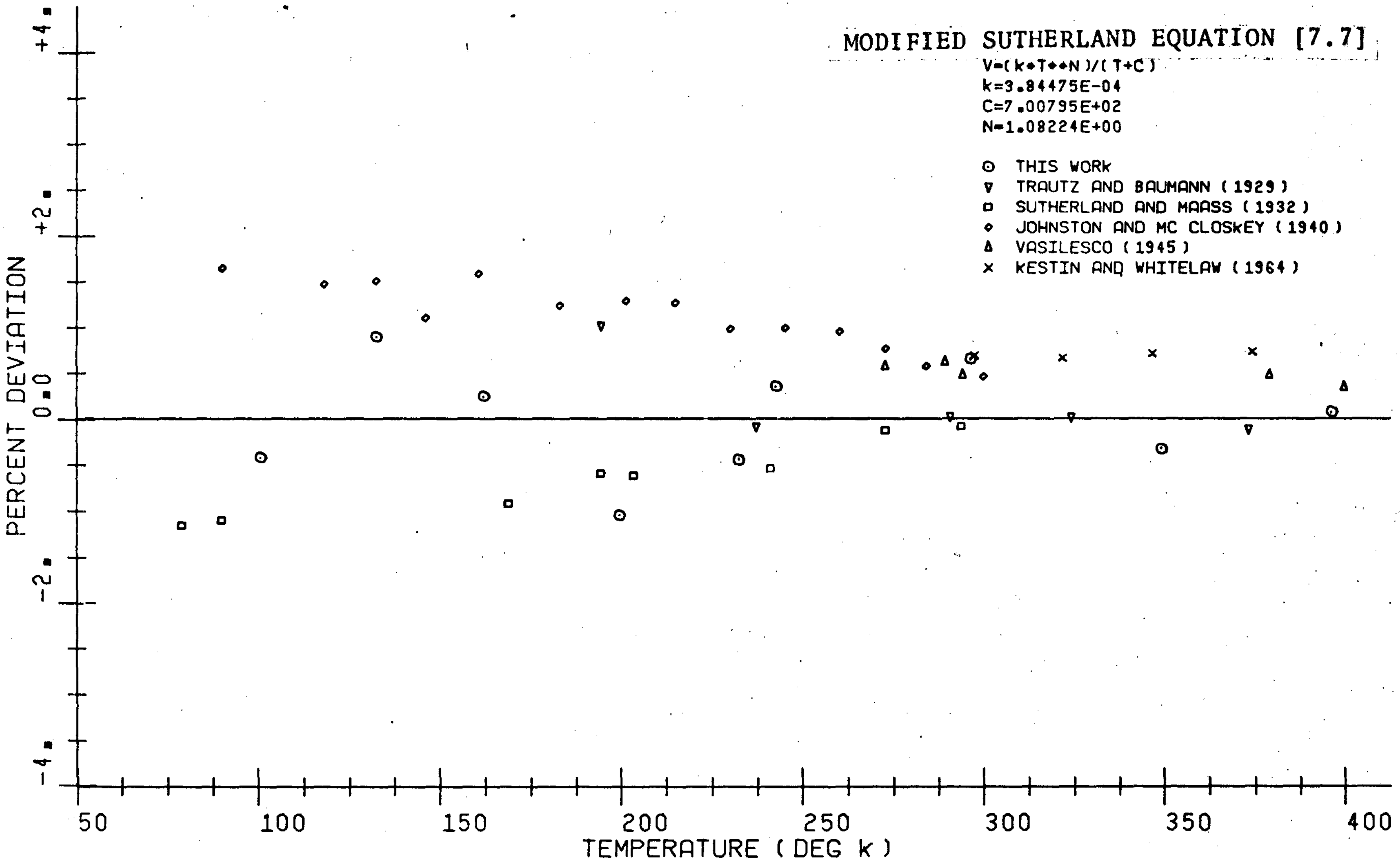


FIGURE 7.8 LOW PRESSURE AIR DEVIATION PLOT

HIGH PRESSURE AIR

A procedure similar to that for nitrogen was carried out for high pressure air, with all the data from references [7], [11], [13], [18] and [19] as well as the data from this work being plotted in the form of excess viscosity vs density. The correlating equation used for all the dense air data was:

$$\eta-\eta_o = 1.02055 \times 10^{-4}\,\rho + 5.96947 \times 10^{-4}\,\rho^2 \text{ POISE} \qquad (7.8)$$

Again a general equation for the viscosity of air as a function of temperature and density can be produced by the summation of equations (7.7) and (7.8) and is of the form:

$$\eta = \frac{3.84475 \times 10^{-4} T^{1.08224}}{T + 700.795} + 1.02055 \times 10^{-4}\rho + 5.96947 \times 10^{-4}\rho^2 \text{ POISE} \qquad (7.9)$$

Figures (7.9) and (7.10) show graphical representations of excess viscosity vs density, with equation (7.8) used to draw the curve, and the deviation plot of $\eta-\eta_{CAL}/\eta$ against density. The deviation plot shows a standard deviation of 1.3% for equation (7.9) from the data, and an overall scatter of +4 and -2%.

The data of Kestin and Whitelaw [13] appears to show a systematic discrepancy from the earlier work of Kestin et al. and from other more recent authors. The work of Lo, Carrol and Stiel [19] correlates excess viscosity as a function of thermal pressure, $\partial P/\partial T$ as well as providing a tabulation of viscosity as a function of pressure and temperature. It was their tabulated values of viscosity rather than any real data points that were used in this present correlation, this was found to be necessary because of the shortage of high density air viscosity data.

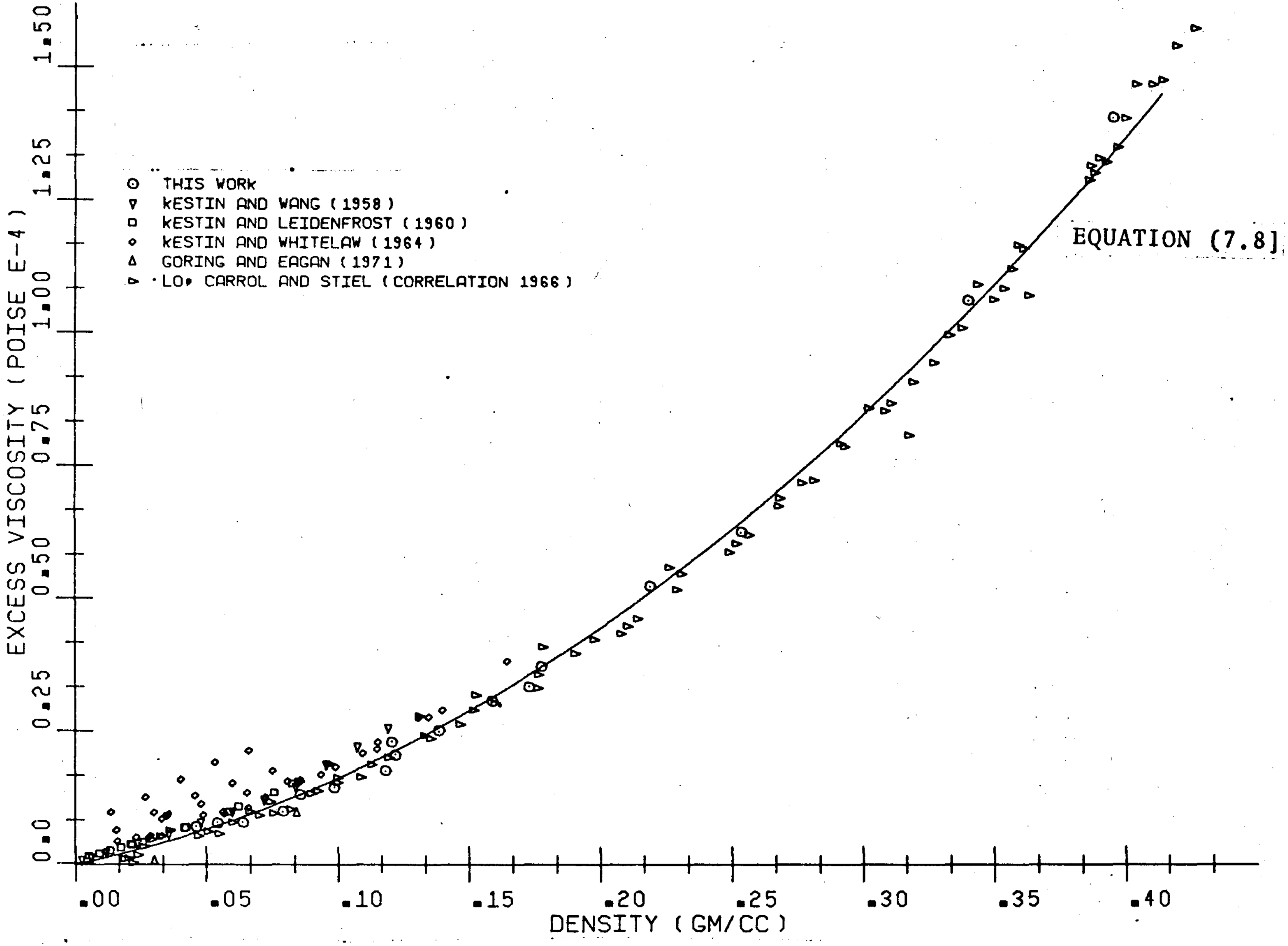


FIGURE 7.9 EXCESS VISCOSITY OF AIR VS DENSITY

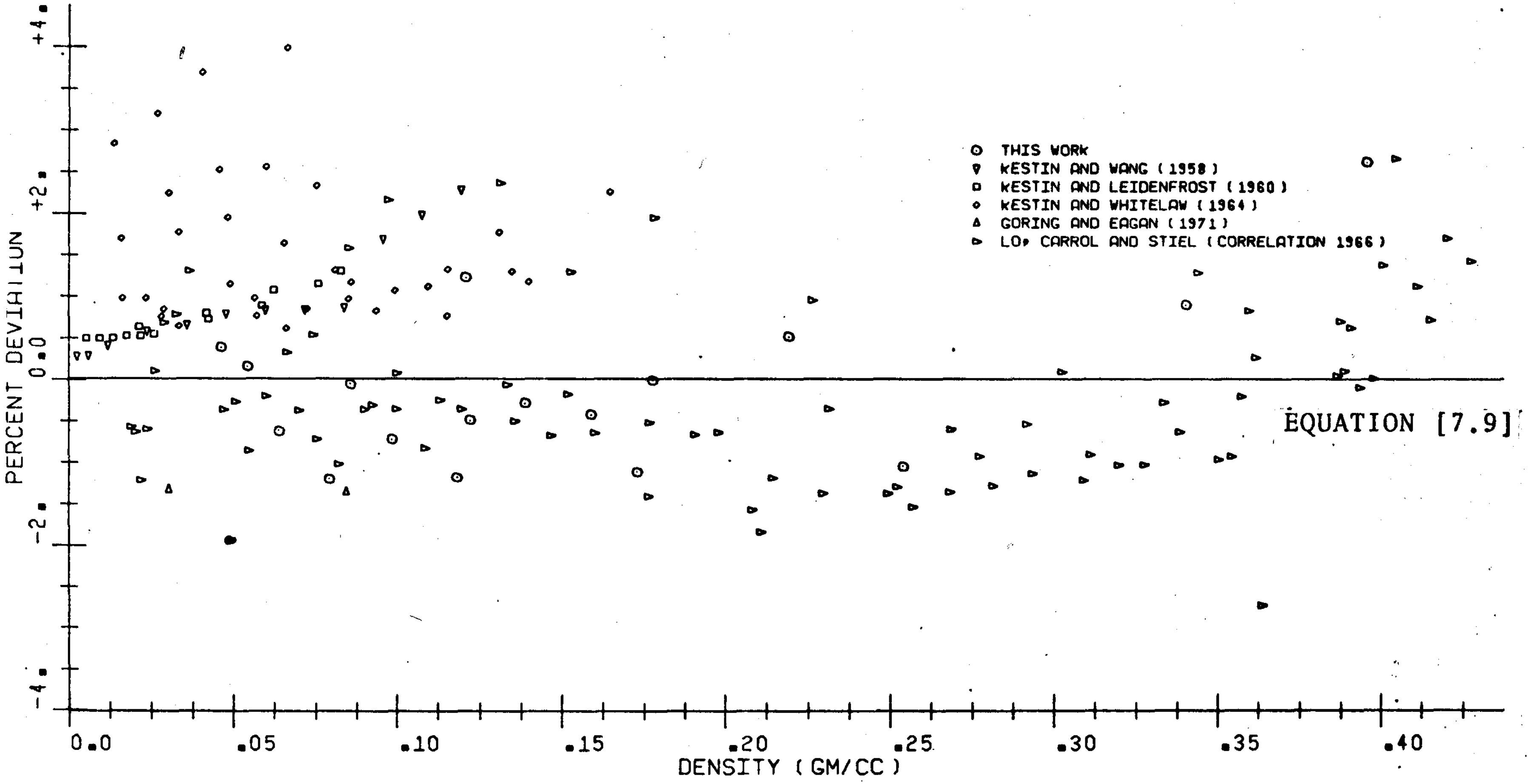


FIGURE 7.10 HIGH PRESSURE AIR DEVIATION PLOT

As in the case of nitrogen, graphical representation of air density and viscosity as functions of temperature and pressure are presented in figures (7.11) and (7.12) respectively, and computed values of air viscosity using equation (7.9) are given in table (7.4).

RECOMMENDATIONS:

If the present apparatus is to be used for further work on the measurement of the viscosity of gases, it is suggested that a thermostated temperature control system be installed. This would allow greater thermal stability to be achieved and would also facilitate the operation of the apparatus.

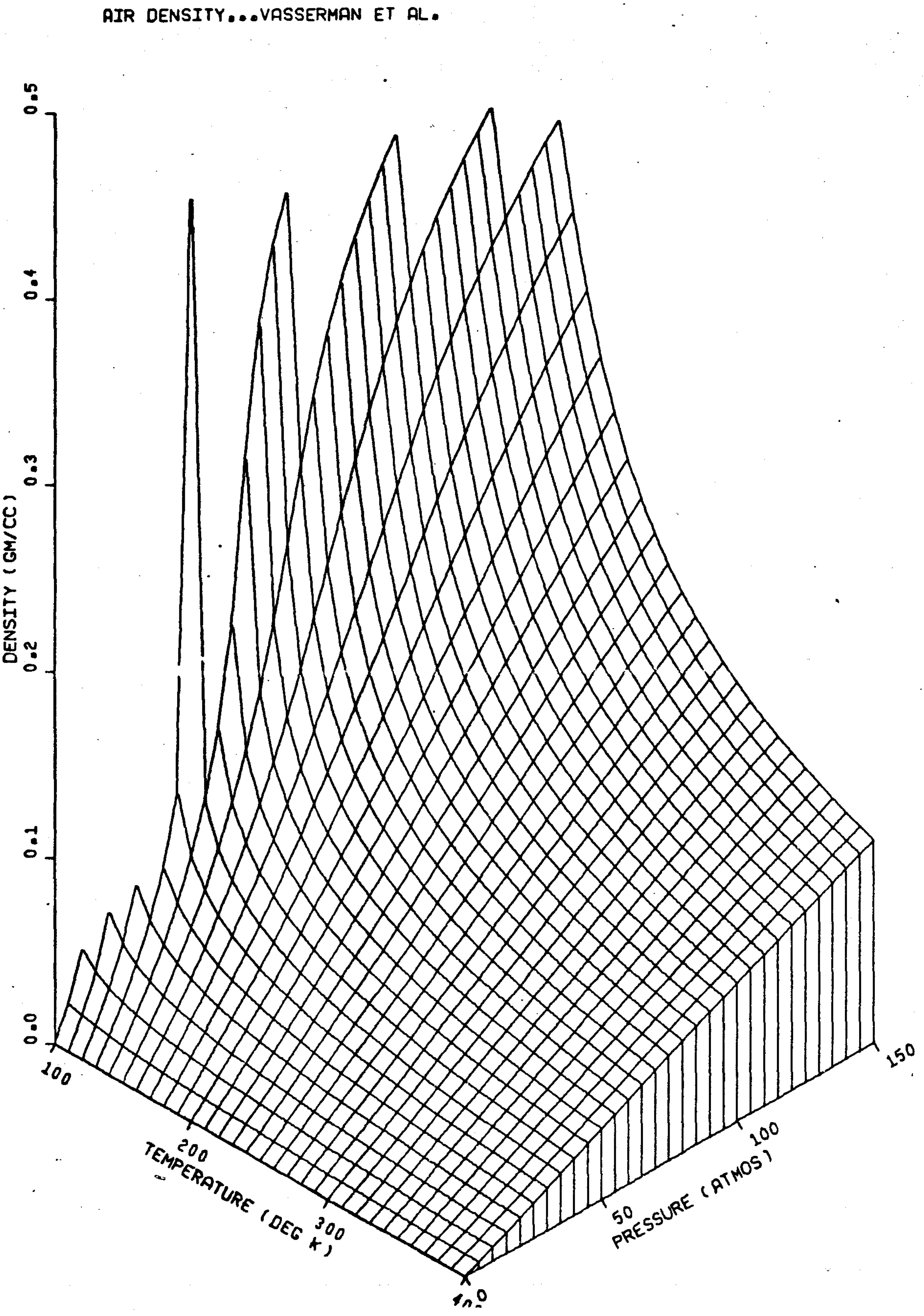


FIGURE 7.11 THE DENSITY OF AIR

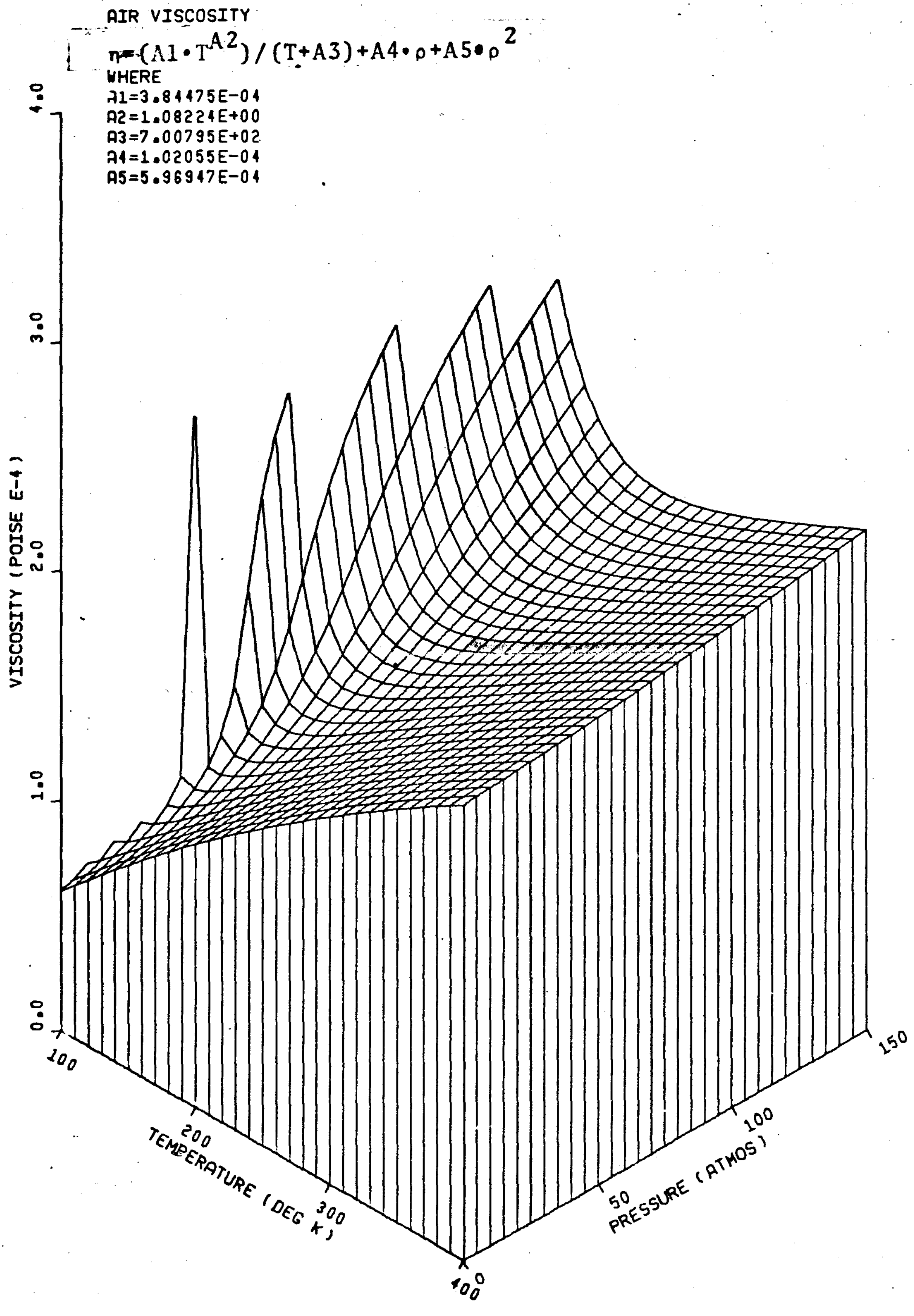


FIGURE 7.12 THE VISCOSITY OF AIR

TABLE 7.3 THE VISCOSITY OF NITROGEN
(POISE)

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 0	5	10	15	20
80	.5502E-04	.5853E-04			
90	.6159E-04	.6417E-04			
100	.6806E-04	.7020E-04	.7411E-04		
110	.7443E-04	.7629E-04	.7912E-04	.8408E-04	
120	.8070E-04	.8235E-04	.8465E-04	.8799E-04	.9328E-04
130	.8688E-04	.8837E-04	.9033E-04	.9294E-04	.9651E-04
140	.9296E-04	.9432E-04	.9604E-04	.9822E-04	.1010E-03
150	.9895E-04	.1002E-03	.1017E-03	.1036E-03	.1059E-03
160	.1048E-03	.1060E-03	.1074E-03	.1091E-03	.1110E-03
170	.1106E-03	.1117E-03	.1130E-03	.1145E-03	.1163E-03
180	.1164E-03	.1174E-03	.1185E-03	.1199E-03	.1215E-03
190	.1220E-03	.1229E-03	.1240E-03	.1253E-03	.1267E-03
200	.1275E-03	.1284E-03	.1294E-03	.1306E-03	.1319E-03
210	.1330E-03	.1338E-03	.1348E-03	.1359E-03	.1371E-03
220	.1383E-03	.1391E-03	.1400E-03	.1411E-03	.1422E-03
230	.1436E-03	.1444E-03	.1452E-03	.1462E-03	.1472E-03
240	.1488E-03	.1496E-03	.1504E-03	.1513E-03	.1523E-03
250	.1539E-03	.1546E-03	.1554E-03	.1563E-03	.1572E-03
260	.1590E-03	.1597E-03	.1604E-03	.1612E-03	.1621E-03
270	.1640E-03	.1646E-03	.1653E-03	.1661E-03	.1669E-03
280	.1689E-03	.1695E-03	.1702E-03	.1709E-03	.1717E-03
290	.1737E-03	.1743E-03	.1749E-03	.1756E-03	.1764E-03
300	.1784E-03	.1790E-03	.1796E-03	.1803E-03	.1810E-03
310	.1831E-03	.1837E-03	.1843E-03	.1849E-03	.1856E-03
320	.1877E-03	.1883E-03	.1889E-03	.1895E-03	.1902E-03
330	.1923E-03	.1928E-03	.1934E-03	.1940E-03	.1946E-03
340	.1968E-03	.1973E-03	.1978E-03	.1984E-03	.1990E-03
350	.2012E-03	.2017E-03	.2022E-03	.2028E-03	.2034E-03
360	.2055E-03	.2060E-03	.2065E-03	.2071E-03	.2077E-03
370	.2098E-03	.2103E-03	.2108E-03	.2113E-03	.2119E-03
380	.2141E-03	.2145E-03	.2150E-03	.2155E-03	.2161E-03
390	.2183E-03	.2187E-03	.2192E-03	.2197E-03	.2202E-03
400	.2224E-03	.2228E-03	.2233E-03	.2237E-03	.2242E-03
410	.2264E-03	.2269E-03	.2273E-03	.2278E-03	.2283E-03
420	.2304E-03	.2308E-03	.2313E-03	.2317E-03	.2322E-03
430	.2344E-03	.2348E-03	.2352E-03	.2357E-03	.2361E-03
440	.2383E-03	.2387E-03	.2391E-03	.2395E-03	.2400E-03
450	.2421E-03	.2425E-03	.2429E-03	.2433E-03	.2438E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS)				
	25	30	35	40	45
120	.1047E-03				
130	.1016E-03	.1096E-03	.1257E-03	.1893E-03	.2550E-03
140	.1046E-03	.1093E-03	.1156E-03	.1247E-03	.1382E-03
150	.1087E-03	.1122E-03	.1165E-03	.1218E-03	.1284E-03
160	.1134E-03	.1162E-03	.1194E-03	.1233E-03	.1278E-03
170	.1183E-03	.1206E-03	.1233E-03	.1263E-03	.1298E-03
180	.1233E-03	.1253E-03	.1276E-03	.1301E-03	.1330E-03
190	.1283E-03	.1301E-03	.1321E-03	.1343E-03	.1367E-03
200	.1334E-03	.1350E-03	.1367E-03	.1387E-03	.1408E-03
210	.1384E-03	.1399E-03	.1414E-03	.1432E-03	.1451E-03
220	.1434E-03	.1447E-03	.1462E-03	.1478E-03	.1495E-03
230	.1484E-03	.1496E-03	.1510E-03	.1524E-03	.1539E-03
240	.1533E-03	.1545E-03	.1557E-03	.1570E-03	.1584E-03
250	.1582E-03	.1593E-03	.1604E-03	.1617E-03	.1630E-03
260	.1630E-03	.1640E-03	.1651E-03	.1663E-03	.1675E-03
270	.1678E-03	.1688E-03	.1698E-03	.1709E-03	.1720E-03
280	.1725E-03	.1734E-03	.1744E-03	.1754E-03	.1765E-03
290	.1772E-03	.1781E-03	.1790E-03	.1799E-03	.1809E-03
300	.1818E-03	.1826E-03	.1835E-03	.1844E-03	.1853E-03
310	.1864E-03	.1871E-03	.1880E-03	.1888E-03	.1897E-03
320	.1909E-03	.1916E-03	.1924E-03	.1932E-03	.1941E-03
330	.1953E-03	.1960E-03	.1967E-03	.1975E-03	.1983E-03
340	.1997E-03	.2004E-03	.2011E-03	.2018E-03	.2026E-03
350	.2040E-03	.2046E-03	.2053E-03	.2060E-03	.2068E-03
360	.2083E-03	.2089E-03	.2095E-03	.2102E-03	.2110E-03
370	.2125E-03	.2131E-03	.2137E-03	.2144E-03	.2151E-03
380	.2166E-03	.2172E-03	.2178E-03	.2185E-03	.2191E-03
390	.2207E-03	.2213E-03	.2219E-03	.2225E-03	.2231E-03
400	.2248E-03	.2253E-03	.2259E-03	.2265E-03	.2271E-03
410	.2288E-03	.2293E-03	.2298E-03	.2304E-03	.2310E-03
420	.2327E-03	.2332E-03	.2338E-03	.2343E-03	.2349E-03
430	.2366E-03	.2371E-03	.2376E-03	.2382E-03	.2387E-03
440	.2404E-03	.2409E-03	.2414E-03	.2420E-03	.2425E-03
450	.2442E-03	.2447E-03	.2452E-03	.2457E-03	.2462E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 50	55	60	65	70
130	.2828E-03				
140	.1585E-03	.1846E-03	.2112E-03	.2343E-03	.2533E-03
150	.1367E-03	.1471E-03	.1597E-03	.1739E-03	.1890E-03
160	.1331E-03	.1394E-03	.1465E-03	.1547E-03	.1638E-03
170	.1338E-03	.1382E-03	.1433E-03	.1488E-03	.1550E-03
180	.1361E-03	.1396E-03	.1435E-03	.1477E-03	.1523E-03
190	.1394E-03	.1423E-03	.1454E-03	.1488E-03	.1525E-03
200	.1431E-03	.1455E-03	.1482E-03	.1511E-03	.1541E-03
210	.1471E-03	.1492E-03	.1516E-03	.1540E-03	.1566E-03
220	.1513E-03	.1532E-03	.1552E-03	.1574E-03	.1597E-03
230	.1556E-03	.1573E-03	.1591E-03	.1611E-03	.1631E-03
240	.1599E-03	.1615E-03	.1632E-03	.1649E-03	.1668E-03
250	.1643E-03	.1658E-03	.1673E-03	.1689E-03	.1706E-03
260	.1688E-03	.1701E-03	.1715E-03	.1730E-03	.1745E-03
270	.1732E-03	.1744E-03	.1757E-03	.1771E-03	.1785E-03
280	.1776E-03	.1788E-03	.1800E-03	.1812E-03	.1826E-03
290	.1820E-03	.1831E-03	.1842E-03	.1854E-03	.1866E-03
300	.1863E-03	.1874E-03	.1884E-03	.1896E-03	.1907E-03
310	.1907E-03	.1916E-03	.1927E-03	.1937E-03	.1948E-03
320	.1949E-03	.1959E-03	.1968E-03	.1978E-03	.1989E-03
330	.1992E-03	.2001E-03	.2010E-03	.2019E-03	.2029E-03
340	.2034E-03	.2042E-03	.2051E-03	.2060E-03	.2070E-03
350	.2076E-03	.2084E-03	.2092E-03	.2101E-03	.2110E-03
360	.2117E-03	.2125E-03	.2133E-03	.2141E-03	.2149E-03
370	.2158E-03	.2165E-03	.2173E-03	.2181E-03	.2189E-03
380	.2198E-03	.2205E-03	.2212E-03	.2220E-03	.2228E-03
390	.2238E-03	.2245E-03	.2252E-03	.2259E-03	.2267E-03
400	.2277E-03	.2284E-03	.2291E-03	.2298E-03	.2305E-03
410	.2316E-03	.2323E-03	.2329E-03	.2336E-03	.2343E-03
420	.2355E-03	.2361E-03	.2367E-03	.2374E-03	.2380E-03
430	.2393E-03	.2399E-03	.2405E-03	.2411E-03	.2418E-03
440	.2430E-03	.2436E-03	.2442E-03	.2448E-03	.2454E-03
450	.2468E-03	.2473E-03	.2479E-03	.2485E-03	.2491E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 75	80	85	90	95
140	.2689E-03	.2819E-03			
150	.2041E-03	.2185E-03	.2320E-03	.2443E-03	.2556E-03
160	.1736E-03	.1838E-03	.1942E-03	.2045E-03	.2147E-03
170	.1616E-03	.1687E-03	.1762E-03	.1839E-03	.1917E-03
180	.1573E-03	.1625E-03	.1681E-03	.1739E-03	.1800E-03
190	.1564E-03	.1606E-03	.1649E-03	.1695E-03	.1743E-03
200	.1574E-03	.1608E-03	.1644E-03	.1682E-03	.1721E-03
210	.1594E-03	.1623E-03	.1654E-03	.1686E-03	.1719E-03
220	.1621E-03	.1646E-03	.1673E-03	.1700E-03	.1729E-03
230	.1653E-03	.1675E-03	.1698E-03	.1723E-03	.1748E-03
240	.1687E-03	.1707E-03	.1728E-03	.1750E-03	.1772E-03
250	.1723E-03	.1742E-03	.1761E-03	.1780E-03	.1800E-03
260	.1761E-03	.1778E-03	.1795E-03	.1813E-03	.1831E-03
270	.1800E-03	.1815E-03	.1831E-03	.1846E-03	.1865E-03
280	.1839E-03	.1854E-03	.1868E-03	.1884E-03	.1899E-03
290	.1879E-03	.1892E-03	.1906E-03	.1920E-03	.1935E-03
300	.1919E-03	.1932E-03	.1944E-03	.1958E-03	.1971E-03
310	.1959E-03	.1971E-03	.1983E-03	.1995E-03	.2008E-03
320	.1999E-03	.2010E-03	.2022E-03	.2033E-03	.2045E-03
330	.2039E-03	.2050E-03	.2060E-03	.2071E-03	.2083E-03
340	.2079E-03	.2089E-03	.2099E-03	.2110E-03	.2120E-03
350	.2119E-03	.2128E-03	.2138E-03	.2148E-03	.2158E-03
360	.2158E-03	.2167E-03	.2176E-03	.2186E-03	.2195E-03
370	.2197E-03	.2206E-03	.2214E-03	.2223E-03	.2233E-03
380	.2236E-03	.2244E-03	.2252E-03	.2261E-03	.2270E-03
390	.2274E-03	.2282E-03	.2290E-03	.2298E-03	.2307E-03
400	.2312E-03	.2320E-03	.2328E-03	.2335E-03	.2344E-03
410	.2350E-03	.2357E-03	.2365E-03	.2372E-03	.2380E-03
420	.2387E-03	.2394E-03	.2401E-03	.2409E-03	.2416E-03
430	.2424E-03	.2431E-03	.2438E-03	.2445E-03	.2452E-03
440	.2461E-03	.2467E-03	.2474E-03	.2481E-03	.2488E-03
450	.2497E-03	.2503E-03	.2510E-03	.2516E-03	.2523E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 100	105	110	115	120
150	.2659E-03	.2754E-03	.2840E-03	.2920E-03	
160	.2244E-03	.2338E-03	.2427E-03	.2512E-03	.2592E-03
170	.1996E-03	.2074E-03	.2151E-03	.2227E-03	.2301E-03
180	.1861E-03	.1924E-03	.1987E-03	.2050E-03	.2113E-03
190	.1793E-03	.1843E-03	.1895E-03	.1947E-03	.2000E-03
200	.1761E-03	.1803E-03	.1846E-03	.1890E-03	.1934E-03
210	.1753E-03	.1788E-03	.1824E-03	.1862E-03	.1899E-03
220	.1759E-03	.1789E-03	.1820E-03	.1852E-03	.1885E-03
230	.1774E-03	.1800E-03	.1828E-03	.1856E-03	.1885E-03
240	.1795E-03	.1819E-03	.1843E-03	.1868E-03	.1894E-03
250	.1821E-03	.1843E-03	.1865E-03	.1887E-03	.1910E-03
260	.1850E-03	.1870E-03	.1890E-03	.1910E-03	.1931E-03
270	.1882E-03	.1900E-03	.1918E-03	.1937E-03	.1956E-03
280	.1915E-03	.1932E-03	.1948E-03	.1966E-03	.1983E-03
290	.1950E-03	.1965E-03	.1981E-03	.1997E-03	.2013E-03
300	.1985E-03	.1999E-03	.2014E-03	.2029E-03	.2044E-03
310	.2021E-03	.2034E-03	.2048E-03	.2062E-03	.2076E-03
320	.2058E-03	.2070E-03	.2083E-03	.2096E-03	.2109E-03
330	.2094E-03	.2106E-03	.2118E-03	.2131E-03	.2143E-03
340	.2131E-03	.2142E-03	.2154E-03	.2166E-03	.2177E-03
350	.2168E-03	.2179E-03	.2190E-03	.2201E-03	.2212E-03
360	.2205E-03	.2215E-03	.2226E-03	.2236E-03	.2247E-03
370	.2242E-03	.2252E-03	.2262E-03	.2272E-03	.2282E-03
380	.2279E-03	.2288E-03	.2297E-03	.2307E-03	.2317E-03
390	.2315E-03	.2324E-03	.2333E-03	.2342E-03	.2352E-03
400	.2352E-03	.2360E-03	.2369E-03	.2378E-03	.2387E-03
410	.2388E-03	.2396E-03	.2404E-03	.2413E-03	.2421E-03
420	.2424E-03	.2432E-03	.2440E-03	.2448E-03	.2456E-03
430	.2459E-03	.2467E-03	.2475E-03	.2482E-03	.2490E-03
440	.2495E-03	.2502E-03	.2509E-03	.2517E-03	.2525E-03
450	.2530E-03	.2537E-03	.2544E-03	.2551E-03	.2559E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 125	130	135	140	145
160	.2569E-03	.2741E-03	.2809E-03	.2874E-03	.2935E-03
170	.2372E-03	.2442E-03	.2508E-03	.2573E-03	.2635E-03
180	.2175E-03	.2237E-03	.2297E-03	.2356E-03	.2414E-03
190	.2052E-03	.2105E-03	.2157E-03	.2209E-03	.2261E-03
200	.1979E-03	.2024E-03	.2069E-03	.2114E-03	.2160E-03
210	.1938E-03	.1977E-03	.2016E-03	.2055E-03	.2095E-03
220	.1919E-03	.1952E-03	.1987E-03	.2021E-03	.2056E-03
230	.1914E-03	.1944E-03	.1974E-03	.2005E-03	.2036E-03
240	.1920E-03	.1947E-03	.1974E-03	.2001E-03	.2029E-03
250	.1934E-03	.1958E-03	.1982E-03	.2007E-03	.2032E-03
260	.1952E-03	.1974E-03	.1996E-03	.2019E-03	.2042E-03
270	.1975E-03	.1995E-03	.2015E-03	.2036E-03	.2057E-03
280	.2001E-03	.2020E-03	.2038E-03	.2057E-03	.2076E-03
290	.2029E-03	.2046E-03	.2064E-03	.2081E-03	.2099E-03
300	.2059E-03	.2075E-03	.2091E-03	.2108E-03	.2124E-03
310	.2091E-03	.2105E-03	.2120E-03	.2136E-03	.2151E-03
320	.2123E-03	.2137E-03	.2151E-03	.2165E-03	.2180E-03
330	.2156E-03	.2169E-03	.2182E-03	.2196E-03	.2209E-03
340	.2190E-03	.2202E-03	.2214E-03	.2227E-03	.2240E-03
350	.2223E-03	.2235E-03	.2247E-03	.2259E-03	.2271E-03
360	.2258E-03	.2269E-03	.2280E-03	.2292E-03	.2303E-03
370	.2292E-03	.2303E-03	.2313E-03	.2324E-03	.2335E-03
380	.2327E-03	.2337E-03	.2347E-03	.2357E-03	.2368E-03
390	.2361E-03	.2371E-03	.2381E-03	.2390E-03	.2401E-03
400	.2396E-03	.2405E-03	.2414E-03	.2424E-03	.2433E-03
410	.2430E-03	.2439E-03	.2448E-03	.2457E-03	.2466E-03
420	.2464E-03	.2473E-03	.2481E-03	.2490E-03	.2499E-03
430	.2498E-03	.2507E-03	.2515E-03	.2523E-03	.2532E-03
440	.2532E-03	.2540E-03	.2548E-03	.2556E-03	.2564E-03
450	.2566E-03	.2574E-03	.2581E-03	.2589E-03	.2597E-03

TABLE 7.3 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 150	155	160	165	170
170	.2695E-03	.2753E-03	.2809E-03	.2863E-03	.2915E-03
180	.2470E-03	.2525E-03	.2579E-03	.2631E-03	.2682E-03
190	.2312E-03	.2362E-03	.2411E-03	.2459E-03	.2507E-03
200	.2204E-03	.2249E-03	.2293E-03	.2337E-03	.2381E-03
210	.2135E-03	.2174E-03	.2214E-03	.2253E-03	.2292E-03
220	.2091E-03	.2127E-03	.2162E-03	.2197E-03	.2232E-03
230	.2067E-03	.2099E-03	.2130E-03	.2162E-03	.2194E-03
240	.2057E-03	.2085E-03	.2114E-03	.2142E-03	.2171E-03
250	.2057E-03	.2083E-03	.2108E-03	.2134E-03	.2161E-03
260	.2065E-03	.2088E-03	.2112E-03	.2135E-03	.2159E-03
270	.2078E-03	.2099E-03	.2121E-03	.2143E-03	.2165E-03
280	.2096E-03	.2116E-03	.2135E-03	.2156E-03	.2176E-03
290	.2117E-03	.2135E-03	.2154E-03	.2172E-03	.2191E-03
300	.2141E-03	.2158E-03	.2175E-03	.2193E-03	.2210E-03
310	.2167E-03	.2183E-03	.2199E-03	.2215E-03	.2232E-03
320	.2194E-03	.2209E-03	.2224E-03	.2240E-03	.2255E-03
330	.2223E-03	.2237E-03	.2252E-03	.2266E-03	.2280E-03
340	.2253E-03	.2266E-03	.2280E-03	.2293E-03	.2307E-03
350	.2284E-03	.2296E-03	.2309E-03	.2322E-03	.2335E-03
360	.2315E-03	.2327E-03	.2339E-03	.2351E-03	.2363E-03
370	.2347E-03	.2358E-03	.2369E-03	.2381E-03	.2393E-03
380	.2379E-03	.2389E-03	.2400E-03	.2411E-03	.2423E-03
390	.2411E-03	.2421E-03	.2432E-03	.2442E-03	.2453E-03
400	.2443E-03	.2453E-03	.2463E-03	.2473E-03	.2483E-03
410	.2475E-03	.2485E-03	.2495E-03	.2504E-03	.2514E-03
420	.2508E-03	.2517E-03	.2526E-03	.2536E-03	.2545E-03
430	.2540E-03	.2549E-03	.2558E-03	.2567E-03	.2576E-03
440	.2573E-03	.2581E-03	.2590E-03	.2598E-03	.2607E-03
450	.2605E-03	.2613E-03	.2621E-03	.2630E-03	.2638E-03

TABLE 7.4 THE VISCOSITY OF AIR
(POISE)

TEMPERATURE (DEG K)	PRESSURE (ATMOS)				
	0	5	10	15	20
80	.5648F-04	.6010E-04			
90	.6335F-04	.6608E-04			
100	.7012F-04	.7239E-04	.7653F-04		
110	.7678F-04	.7875F-04	.8173F-04	.8720E-04	
120	.8333F-04	.8508E-04	.8750F-04	.9104E-04	.9700F-04
130	.8978F-04	.9136E-04	.9342F-04	.9616E-04	.9996E-04
140	.9612F-04	.9756E-04	.9937F-04	.1016E-03	.1046F-03
150	.1024F-03	.1037F-03	.1053F-03	.1073E-03	.1097F-03
160	.1085F-03	.1097E-03	.1112F-03	.1129E-03	.1150E-03
170	.1145F-03	.1157E-03	.1170F-03	.1186E-03	.1204F-03
180	.1204F-03	.1215E-03	.1228F-03	.1242E-03	.1258F-03
190	.1263F-03	.1273E-03	.1284F-03	.1297E-03	.1312F-03
200	.1320F-03	.1329E-03	.1340F-03	.1352E-03	.1366F-03
210	.1376F-03	.1385F-03	.1395F-03	.1407E-03	.1419E-03
220	.1431F-03	.1440E-03	.1450F-03	.1460E-03	.1472F-03
230	.1486F-03	.1494E-03	.1503E-03	.1513E-03	.1524E-03
240	.1539F-03	.1547E-03	.1556F-03	.1565E-03	.1575F-03
250	.1592F-03	.1599F-03	.1608F-03	.1617E-03	.1626F-03
260	.1644F-03	.1651E-03	.1659F-03	.1667E-03	.1676F-03
270	.1695F-03	.1702E-03	.1709F-03	.1717E-03	.1726E-03
280	.1745F-03	.1751E-03	.1759F-03	.1766E-03	.1774F-03
290	.1794F-03	.1800F-03	.1807F-03	.1815E-03	.1822F-03
300	.1842F-03	.1849E-03	.1855F-03	.1862E-03	.1870F-03
310	.1890E-03	.1896E-03	.1902F-03	.1909E-03	.1916E-03
320	.1937F-03	.1943E-03	.1949F-03	.1955E-03	.1962E-03
330	.1983F-03	.1989E-03	.1995F-03	.2001E-03	.2008F-03
340	.2028F-03	.2034E-03	.2040F-03	.2046E-03	.2052F-03
350	.2073F-03	.2079E-03	.2084F-03	.2090E-03	.2096E-03
360	.2117E-03	.2122E-03	.2128F-03	.2134E-03	.2139E-03
370	.2161E-03	.2166E-03	.2171F-03	.2176E-03	.2182E-03
380	.2203F-03	.2208E-03	.2213F-03	.2219E-03	.2224F-03
390	.2245E-03	.2250E-03	.2255E-03	.2260E-03	.2266E-03
400	.2287F-03	.2291F-03	.2296F-03	.2301E-03	.2307F-03
410	.2328F-03	.2332E-03	.2337F-03	.2342E-03	.2347E-03
420	.2368F-03	.2372E-03	.2377F-03	.2381E-03	.2386F-03
430	.2407F-03	.2412E-03	.2416F-03	.2421E-03	.2426F-03
440	.2446F-03	.2450E-03	.2455F-03	.2459E-03	.2464F-03
450	.2485F-03	.2489E-03	.2493E-03	.2498E-03	.2502F-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 25	30	35	40	45
130	.1056E-03	.1157E-03	.2934E-03		
140	.1084E-03	.1135E-03	.1208E-03	.1322E-03	.1531E-03
150	.1126E-03	.1162E-03	.1208E-03	.1266E-03	.1341E-03
160	.1174E-03	.1203E-03	.1237E-03	.1278E-03	.1326E-03
170	.1225E-03	.1249E-03	.1276E-03	.1308E-03	.1345E-03
180	.1276E-03	.1297E-03	.1321E-03	.1347E-03	.1376E-03
190	.1328E-03	.1347E-03	.1367E-03	.1390E-03	.1415E-03
200	.1381E-03	.1397E-03	.1415E-03	.1435E-03	.1457E-03
210	.1433E-03	.1448E-03	.1464E-03	.1482E-03	.1501E-03
220	.1484E-03	.1498E-03	.1513E-03	.1529E-03	.1546E-03
230	.1536E-03	.1548E-03	.1562E-03	.1577E-03	.1592E-03
240	.1586E-03	.1598E-03	.1611E-03	.1624E-03	.1639E-03
250	.1637E-03	.1648E-03	.1659E-03	.1672E-03	.1685E-03
260	.1686E-03	.1696E-03	.1707E-03	.1719E-03	.1732E-03
270	.1735E-03	.1745E-03	.1755E-03	.1766E-03	.1778E-03
280	.1783E-03	.1792E-03	.1802E-03	.1813E-03	.1823E-03
290	.1831E-03	.1840E-03	.1849E-03	.1859E-03	.1869E-03
300	.1878E-03	.1886E-03	.1895E-03	.1904E-03	.1914E-03
310	.1924E-03	.1932E-03	.1940E-03	.1949E-03	.1958E-03
320	.1970E-03	.1977E-03	.1985E-03	.1994E-03	.2002E-03
330	.2015E-03	.2022E-03	.2030E-03	.2038E-03	.2046E-03
340	.2059E-03	.2066E-03	.2073E-03	.2081E-03	.2089E-03
350	.2103E-03	.2109E-03	.2117E-03	.2124E-03	.2131E-03
360	.2146E-03	.2152E-03	.2159E-03	.2166E-03	.2173E-03
370	.2188E-03	.2195E-03	.2201E-03	.2208E-03	.2215E-03
380	.2230E-03	.2236E-03	.2242E-03	.2249E-03	.2256E-03
390	.2271E-03	.2277E-03	.2283E-03	.2290E-03	.2296E-03
400	.2312E-03	.2318E-03	.2324E-03	.2330E-03	.2336E-03
410	.2352E-03	.2358E-03	.2363E-03	.2369E-03	.2375E-03
420	.2392E-03	.2397E-03	.2402E-03	.2408E-03	.2414E-03
430	.2431E-03	.2436E-03	.2441E-03	.2447E-03	.2452E-03
440	.2469E-03	.2474E-03	.2479E-03	.2485E-03	.2490E-03
450	.2507E-03	.2512E-03	.2517E-03	.2522E-03	.2527E-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 50	55	60	65	70
140	.1965E-03	.2401E-03	.2668E-03	.2854E-03	
150	.1441E-03	.1573E-03	.1742E-03	.1942E-03	.2145E-03
160	.1384E-03	.1453E-03	.1534E-03	.1629E-03	.1737E-03
170	.1386E-03	.1433E-03	.1487E-03	.1547E-03	.1615E-03
180	.1409E-03	.1446E-03	.1486E-03	.1530E-03	.1579E-03
190	.1442E-03	.1472E-03	.1504E-03	.1540E-03	.1578E-03
200	.1480E-03	.1506E-03	.1533E-03	.1562E-03	.1594E-03
210	.1522E-03	.1544E-03	.1567E-03	.1593E-03	.1619E-03
220	.1565E-03	.1584E-03	.1605E-03	.1627E-03	.1651E-03
230	.1609E-03	.1627E-03	.1645E-03	.1665E-03	.1686E-03
240	.1654E-03	.1670E-03	.1687E-03	.1705E-03	.1724E-03
250	.1699E-03	.1714E-03	.1729E-03	.1746E-03	.1763E-03
260	.1745E-03	.1758E-03	.1773E-03	.1787E-03	.1803E-03
270	.1790E-03	.1802E-03	.1816E-03	.1830E-03	.1844E-03
280	.1835E-03	.1847E-03	.1859E-03	.1872E-03	.1885E-03
290	.1880E-03	.1891E-03	.1902E-03	.1914E-03	.1927E-03
300	.1924E-03	.1934E-03	.1945E-03	.1957E-03	.1968E-03
310	.1968E-03	.1978E-03	.1988E-03	.1999E-03	.2010E-03
320	.2012E-03	.2021E-03	.2031E-03	.2041E-03	.2051E-03
330	.2055E-03	.2064E-03	.2073E-03	.2083E-03	.2092E-03
340	.2097E-03	.2106E-03	.2115E-03	.2124E-03	.2133E-03
350	.2139E-03	.2148E-03	.2156E-03	.2165E-03	.2174E-03
360	.2181E-03	.2189E-03	.2197E-03	.2205E-03	.2214E-03
370	.2222E-03	.2230E-03	.2237E-03	.2245E-03	.2254E-03
380	.2263E-03	.2270E-03	.2277E-03	.2285E-03	.2293E-03
390	.2303E-03	.2310E-03	.2317E-03	.2324E-03	.2332E-03
400	.2343E-03	.2349E-03	.2356E-03	.2363E-03	.2370E-03
410	.2382E-03	.2388E-03	.2395E-03	.2402E-03	.2409E-03
420	.2420E-03	.2426E-03	.2433E-03	.2439E-03	.2446E-03
430	.2458E-03	.2464E-03	.2471E-03	.2477E-03	.2483E-03
440	.2496E-03	.2502E-03	.2508E-03	.2514E-03	.2520E-03
450	.2533E-03	.2539E-03	.2544E-03	.2550E-03	.2557E-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS)				
	75	80	85	90	95
150	.2332E-03	.2494E-03	.2635E-03	.2757E-03	.2865E-03
160	.1856E-03	.1981E-03	.2108E-03	.2231E-03	.2347E-03
170	.1689E-03	.1769E-03	.1854E-03	.1942E-03	.2032E-03
180	.1632E-03	.1688E-03	.1748E-03	.1812E-03	.1878E-03
190	.1619E-03	.1662E-03	.1708E-03	.1757E-03	.1809E-03
200	.1627E-03	.1663E-03	.1700E-03	.1739E-03	.1780E-03
210	.1648E-03	.1677E-03	.1709E-03	.1742E-03	.1776E-03
220	.1675E-03	.1701E-03	.1728E-03	.1756E-03	.1786E-03
230	.1708E-03	.1730E-03	.1754E-03	.1779E-03	.1805E-03
240	.1743E-03	.1763E-03	.1785E-03	.1807E-03	.1829E-03
250	.1780E-03	.1799E-03	.1818E-03	.1838E-03	.1858E-03
260	.1819E-03	.1836E-03	.1854E-03	.1872E-03	.1890E-03
270	.1859E-03	.1874E-03	.1891E-03	.1907E-03	.1924E-03
280	.1899E-03	.1914E-03	.1928E-03	.1944E-03	.1960E-03
290	.1940E-03	.1953E-03	.1967E-03	.1981E-03	.1996E-03
300	.1981E-03	.1993E-03	.2006E-03	.2019E-03	.2033E-03
310	.2021E-03	.2033E-03	.2045E-03	.2058E-03	.2071E-03
320	.2062E-03	.2073E-03	.2085E-03	.2096E-03	.2108E-03
330	.2103E-03	.2113E-03	.2124E-03	.2135E-03	.2146E-03
340	.2143E-03	.2153E-03	.2163E-03	.2174E-03	.2184E-03
350	.2183E-03	.2192E-03	.2202E-03	.2212E-03	.2222E-03
360	.2223E-03	.2232E-03	.2241E-03	.2251E-03	.2260E-03
370	.2262E-03	.2271E-03	.2280E-03	.2289E-03	.2298E-03
380	.2301E-03	.2309E-03	.2318E-03	.2326E-03	.2335E-03
390	.2340E-03	.2348E-03	.2356E-03	.2364E-03	.2373E-03
400	.2378E-03	.2386E-03	.2393E-03	.2401E-03	.2409E-03
410	.2416E-03	.2423E-03	.2431E-03	.2438E-03	.2446E-03
420	.2453E-03	.2460E-03	.2467E-03	.2475E-03	.2482E-03
430	.2490E-03	.2497E-03	.2504E-03	.2511E-03	.2518E-03
440	.2527E-03	.2533E-03	.2540E-03	.2547E-03	.2554E-03
450	.2563E-03	.2569E-03	.2576E-03	.2582E-03	.2589E-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 100	105	110	115	120
150	.2962E-03				
160	.2457E-03	.2559E-03	.2653E-03	.2741E-03	.2822E-03
170	.2123E-03	.2213E-03	.2300E-03	.2384E-03	.2466E-03
180	.1947E-03	.2017E-03	.2087E-03	.2157E-03	.2227E-03
190	.1861E-03	.1915E-03	.1971E-03	.2028E-03	.2085E-03
200	.1823E-03	.1867E-03	.1912E-03	.1958E-03	.2005E-03
210	.1811E-03	.1848E-03	.1886E-03	.1924E-03	.1964E-03
220	.1816E-03	.1847E-03	.1880E-03	.1913E-03	.1947E-03
230	.1831E-03	.1858E-03	.1887E-03	.1915E-03	.1945E-03
240	.1853E-03	.1877E-03	.1902E-03	.1928E-03	.1954E-03
250	.1880E-03	.1901E-03	.1924E-03	.1946E-03	.1970E-03
260	.1909E-03	.1929E-03	.1949E-03	.1970E-03	.1991E-03
270	.1942E-03	.1960E-03	.1978E-03	.1997E-03	.2017E-03
280	.1976E-03	.1992E-03	.2009E-03	.2027E-03	.2045E-03
290	.2011E-03	.2026E-03	.2042E-03	.2058E-03	.2075E-03
300	.2047E-03	.2061E-03	.2076E-03	.2091E-03	.2106E-03
310	.2084E-03	.2097E-03	.2111E-03	.2125E-03	.2139E-03
320	.2121E-03	.2133E-03	.2146E-03	.2159E-03	.2173E-03
330	.2158E-03	.2170E-03	.2182E-03	.2194E-03	.2207E-03
340	.2195E-03	.2207E-03	.2218E-03	.2230E-03	.2242E-03
350	.2233E-03	.2243E-03	.2254E-03	.2265E-03	.2277E-03
360	.2270E-03	.2280E-03	.2291E-03	.2301E-03	.2312E-03
370	.2307E-03	.2317E-03	.2327E-03	.2337E-03	.2347E-03
380	.2344E-03	.2354E-03	.2363E-03	.2373E-03	.2382E-03
390	.2381E-03	.2390E-03	.2399E-03	.2408E-03	.2417E-03
400	.2418E-03	.2426E-03	.2435E-03	.2444E-03	.2453E-03
410	.2454E-03	.2462E-03	.2470E-03	.2479E-03	.2487E-03
420	.2490E-03	.2498E-03	.2506E-03	.2514E-03	.2522E-03
430	.2526E-03	.2533E-03	.2541E-03	.2549E-03	.2557E-03
440	.2561E-03	.2568E-03	.2576E-03	.2583E-03	.2591E-03
450	.2596E-03	.2603E-03	.2610E-03	.2617E-03	.2625E-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS) 150	155	160	165	170
170	.2882E-03	.2941E-03	.2997E-03	.3051E-03	
180	.2617E-03	.2675E-03	.2732E-03	.2787E-03	.2840E-03
190	.2425E-03	.2479E-03	.2532E-03	.2584E-03	.2635E-03
200	.2296E-03	.2344E-03	.2392E-03	.2439E-03	.2485E-03
210	.2213E-03	.2255E-03	.2297E-03	.2339E-03	.2381E-03
220	.2162E-03	.2199E-03	.2236E-03	.2273E-03	.2310E-03
230	.2134E-03	.2166E-03	.2199E-03	.2232E-03	.2266E-03
240	.2121E-03	.2150E-03	.2180E-03	.2209E-03	.2239E-03
250	.2120E-03	.2146E-03	.2173E-03	.2199E-03	.2226E-03
260	.2127E-03	.2151E-03	.2175E-03	.2199E-03	.2224E-03
270	.2140E-03	.2162E-03	.2184E-03	.2206E-03	.2229E-03
280	.2158E-03	.2178E-03	.2198E-03	.2219E-03	.2240E-03
290	.2180E-03	.2198E-03	.2217E-03	.2236E-03	.2255E-03
300	.2204E-03	.2221E-03	.2238E-03	.2256E-03	.2274E-03
310	.2230E-03	.2246E-03	.2262E-03	.2279E-03	.2295E-03
320	.2258E-03	.2273E-03	.2288E-03	.2304E-03	.2319E-03
330	.2287E-03	.2302E-03	.2316E-03	.2330E-03	.2345E-03
340	.2318E-03	.2331E-03	.2344E-03	.2358E-03	.2372E-03
350	.2349E-03	.2361E-03	.2374E-03	.2387E-03	.2400E-03
360	.2380E-03	.2392E-03	.2404E-03	.2416E-03	.2429E-03
370	.2412E-03	.2423E-03	.2435E-03	.2446E-03	.2458E-03
380	.2444E-03	.2455E-03	.2466E-03	.2477E-03	.2488E-03
390	.2476E-03	.2487E-03	.2497E-03	.2508E-03	.2518E-03
400	.2509E-03	.2519E-03	.2529E-03	.2539E-03	.2549E-03
410	.2541E-03	.2551E-03	.2560E-03	.2570E-03	.2580E-03
420	.2574E-03	.2583E-03	.2592E-03	.2602E-03	.2611E-03
430	.2606E-03	.2615E-03	.2624E-03	.2633E-03	.2642E-03
440	.2639E-03	.2647E-03	.2656E-03	.2664E-03	.2673E-03
450	.2671E-03	.2679E-03	.2687E-03	.2695E-03	.2704E-03

TABLE 7.4 CONT'D

TEMPERATURE (DEG K)	PRESSURE (ATMOS)				
	125	130	135	140	145
160	.2898E-03	.2970E-03			
170	.2543E-03	.2618E-03	.2688E-03	.2756E-03	.2821E-03
180	.2296E-03	.2364E-03	.2430E-03	.2494E-03	.2557E-03
190	.2143E-03	.2200E-03	.2258E-03	.2314E-03	.2370E-03
200	.2053E-03	.2102E-03	.2150E-03	.2199E-03	.2248E-03
210	.2004E-03	.2045E-03	.2087E-03	.2129E-03	.2171E-03
220	.1981E-03	.2017E-03	.2052E-03	.2089E-03	.2125E-03
230	.1975E-03	.2006E-03	.2037E-03	.2069E-03	.2101E-03
240	.1981E-03	.2008E-03	.2035E-03	.2064E-03	.2092E-03
250	.1994E-03	.2018E-03	.2043E-03	.2068E-03	.2094E-03
260	.2013E-03	.2035E-03	.2058E-03	.2080E-03	.2104E-03
270	.2036E-03	.2056E-03	.2077E-03	.2098E-03	.2119E-03
280	.2063E-03	.2081E-03	.2100E-03	.2119E-03	.2139E-03
290	.2091E-03	.2109E-03	.2126E-03	.2144E-03	.2162E-03
300	.2122E-03	.2138E-03	.2154E-03	.2170E-03	.2187E-03
310	.2154E-03	.2169E-03	.2184E-03	.2199E-03	.2214E-03
320	.2186E-03	.2200E-03	.2214E-03	.2229E-03	.2243E-03
330	.2220E-03	.2233E-03	.2246E-03	.2260E-03	.2274E-03
340	.2254E-03	.2266E-03	.2279E-03	.2292E-03	.2304E-03
350	.2288E-03	.2300E-03	.2312E-03	.2324E-03	.2336E-03
360	.2323E-03	.2334E-03	.2345E-03	.2357E-03	.2368E-03
370	.2358E-03	.2368E-03	.2379E-03	.2390E-03	.2401E-03
380	.2392E-03	.2402E-03	.2413E-03	.2423E-03	.2433E-03
390	.2427E-03	.2437E-03	.2446E-03	.2456E-03	.2466E-03
400	.2462E-03	.2471E-03	.2480E-03	.2490E-03	.2499E-03
410	.2496E-03	.2505E-03	.2514E-03	.2523E-03	.2532E-03
420	.2530E-03	.2539E-03	.2547E-03	.2556E-03	.2565E-03
430	.2565E-03	.2573E-03	.2581E-03	.2589E-03	.2598E-03
440	.2598E-03	.2606E-03	.2614E-03	.2622E-03	.2631E-03
450	.2632E-03	.2640E-03	.2647E-03	.2655E-03	.2663E-03

CHAPTER 8

CONCLUSIONS

1. A series capillary viscometer was used to measure the viscosity of nitrogen and air over the temperature of 100 to 400°K and up to a pressure of 150 atmospheres.

2. The results have been compared with results of previous workers and appear to agree quite favorably. An equation of the form:

$$\eta = \frac{C_1 T^{C_2}}{T+C_3} + C_4 \rho + C_5 \rho^2$$

has been fitted to the two sets of data and is believed accurate to ±1.5% at the most unfavorable conditions of high density.

3. The dilute nitrogen data have also been correlated using the Chapman - Enskog Collision theory, yielding intermolecular force constants.

4. It is apparent that the series capillary viscometer is a excellent primary instrument and is capable of producing accurate data over a broad range of pressures and temperatures.

APPENDIX A1

SAMPLE CALCULATIONS

An air viscosity reading taken at the test temperature of T = 162.26°K and at a pressure of 1.22 atmospheres was chosen arbitrarily to illustrate a typical calculation. Commencing with the flow equation,

$$\eta = \frac{\pi D_1^{\,4} g(1+3\alpha\Delta T)}{128\ Q(L_1-L_2)} \{\Delta P_1\rho_1-(\frac{D_2}{D_1})^4\ \Delta P_2\rho_2\} \qquad \text{(A1.1)}$$

the readings of the variables used were as follows:

THE CAPILLARY DIMENSIONS

L_1 = 53.162 cm

L_2 = 5.161 cm

D_1 = 0.0500312 cm

D_2 = 0.0501366 cm

THE ACCELERATION DUE TO GRAVITY

The acceleration due to gravity 'g' in the Hamilton area is 980.3941 cm/sec^2.

THERMAL EXPANSION CORRECTION

The coefficient of thermal expansion 'α' of glass is 3.3×10^{-6}, while the temperature at which the glass capillaries were calibrated was 297.15°K.

TEMPERATURE READINGS

Thermocouple readings, T4 and T5, were taken inside the viscometer cell, T7 and T8, in the volumeter and T9 at the manometer. These were read twice during each experimental run, before and after the pressure readings, manually corrected and tabulated as follows:

TABLE (A1.1) TEMPERATURES DURING SAMPLE RUN

Thermocouple number	4	5	7	8	9
EMF Before	-3.648	-3.645	1.011	1.019	1.028
EMF After	-3.652	-3.639	1.012	1.019	1.029
Average	-3.650	-3.642	1.012	1.019	1.029
Correction	+.002	+.010	+.006	.005	
Corrected EMF	-3.648	-3.632	1.018 1.021	1.024	1.029
Temperature (°K)	162.26	162.85	298.92		299.12

The temperature at T4 = 162.26°K was used as the reference temperature for this run.

ATMOSPHERIC AND PLENUM PRESSURE READINGS

During this run the atmospheric pressure, automatically corrected for non-standard condition was 29.90 in Hg by converting to centimeters and using 13.5955 gm/cm^3 as the density of mercury at 0°C, the atmospheric pressure was found to be:

$$P_A = 29.90 \times 2.54 \times 13.5955$$
$$= 1032.52 \text{ gmf/cm}^2$$

The pressure head between the viscometer plenum and ambient conditions was 17.60 cm Hg at 20°C. The density of mercury at this temperature is 13.545 gm/cm^3. Thus:

$$\begin{aligned}\Delta P_{ENT} &= 17.60 \text{ x } 13.545 \\ &= 238.39 \text{ gmf/cm}^2\end{aligned}$$

Summing the atmospheric and the plenum gauge pressures the total plenum pressure can be determined as:

$$\begin{aligned}P_{PLEN} &= 1032.53 + 238.39 \\ &= 1270.91 \text{ gmf/cm}^2\end{aligned}$$

AIR DENSITY

The air densities were determined using an equation of state given in reference [21] and of the form $\rho = P/ZRT$ where Z, the compressibility factor, was a function of ρ and T. Although this required an iterative solution, a unique value of density could be determined with a knowledge of the pressure and temperature. For a further description of the equation of state and of the method of computation the reader is referred to appendix A2.

MANOMETER AIR DENSITY

A manometer gas density of $\rho_{GAS} = 0.14263 \times 10^{-2}$ gm/cm^3 was computed using 299.12°K and 1270.91 gmf/cm^2 as the state variables.

DIFFERENTIAL PRESSURE READINGS

The pressure drops across the capillaries were calculated from the individual manometer oil level measurements, that is

$$\Delta h_1 = 96.305 - 74.071$$
$$= 22.234 \text{ cm oil}$$
$$\Delta h_2 = 98.667 - 96.305$$
$$= 2.362 \text{ cm oil}$$

The specific weight of the manometer oil was determined using the density of water of 0.9970 gmf/cm^3 at the manometer temperature of 26°C, and the specific gravity of .821, for the manometer oil: thus:

$$\rho_{OIL} = .9970 \times .821$$
$$= .8185$$

The differential pressures, across capillaries one and two can now be calculated by means of the following equations:

$$\Delta P_1 = \Delta h_1 \times (\rho_{OIL} - \rho_{GAS})$$
$$= 22.234 \times (.8185 - .00142)$$
$$= 18.171 \text{ gmf/cm}^2$$
$$\Delta P_2 = 2.362 \times (.8185 - .00142)$$
$$= 1.930 \text{ gmf/cm}^2$$

CAPILLARY GAS DENSITIES

In order to calculate the mean density of the gas in the two capillaries it is necessary to know the average pressure. 'P_{AV}' in each of the capillaries. Therefore:

$$P_{AV1} = P_{PLEN} - \Delta P_1/2.0$$
$$= 1270.91 - 18.171/2.0$$
$$= 1261.83 \text{ gmf/cm}^2$$

$$P_{AV2} = P_{PLEN} - \Delta P_1 - \Delta P_2/2.0$$
$$= 1270.91 - 18.171 - 1.930/20$$
$$= 1251.78 \text{ gmf/cm}^2$$

Using the equation of state previously mentioned and T4 and T5 as the temperatures in capillaries 1 and 2 respectively, the gas densities were computed as follows:

$$\rho_1 = 0.267227 \times 10^{-2} \text{ gm/cm}^3$$
$$\rho_2 = 0.264103 \times 10^{-2} \text{ gm/cm}^3$$

THE MASS FLOW RATE

A pressure head of 5.0 cm of oil was measured between the volumeter and atmospheric conditions. Knowing the density of water and specific gravity of oil to be 0.9981 gm/cm^3 and 0.821 respectively, as well as the ambient atmospheric pressure, the total volumeter pressure was determined to be:

$$P_{VOL} = (5.0 \times .9981 \times .821) + 1032.52$$
$$= 1036.62 \text{ gmf/cm}^2$$

A gas density of 0.118495 x 10^{-2} gm/cm^3 was calculated using 298.92°K and the previously calculated pressure as the state variables.

Since the volume displaced was previously calibrated as 801.924 cm^3 and the time taken for the volumeter piston to traverse this volume was measured at 768.56 sec. Then the mass flow rate could be determined as follows:

$$Q = V \times \rho_{VOL}/\tau$$
$$= 801.924 \times .118495 \times 10^{-2}/768.56$$
$$= 0.123639 \times 10^{-2} \text{ gm/sec}$$

ABSOLUTE VISCOSITY

The absolute viscosity can now be calculated from working equation (3.15) as:

$$\eta = \frac{\pi \times .0500312^4 \times 980.3941\,(1+3 \times 3.3 \times 10^{-6} \times (162.26-297.15))}{128 \times .123639 \times 10^{-2}\,(53.162-5.161)}$$

$$\{18.171 \times 0.267227 \times 10^{-2} - \frac{(0.501366)^4}{(0.500312)} \times$$

$$1.930 \times 0.264103 \times 10^{-2}\}$$

$$= 0.110125 \times 10^{-3} \text{ gm/cm sec}$$

REYNOLDS NUMBER

The mean Reynolds number may be estimated from:

$$R_e = \frac{4Q}{\pi D_1 \eta}$$

$$R_e = \frac{4 \times .123639 \times 10^{-2}}{\pi \times 0.0500312 \times 0.110125 \times 10^{-3}} = 285.7$$

This is well below the critical value for laminar flow in these capillaries.

DEVELOPMENT LENGTH

The development length for laminar flow was calculated from:

$$X_{1\%} = 0.065 \times R_e \times D$$

$$= 0.065 \times 285.70 \times 0.05$$

$$= 0.929 \text{ cm}$$

A high speed CDC 6400 digital computer was used to perform these calculations. A listing of the programme along with the output for this sample run are attached to this section.

```
RUN NUMBER  35

RECOMMENDED VALUE OF VISCOSITY              .110368E-03            (DVISC/DT)        .606089E-06      .549
VISCOSITY (GM/CM SEC)                       .110125E-03     -.220
TEMPERATURE (DEG. K)                         162.261111
PRESSURE (ATM)                                 1.216422

VISCOSITY USING ONLY CAP 1 (GM/CM SEC)      .110111E-03     -.233
VISCOSITY USING ONLY CAP 2 (GM/CM SEC)      .109972E-03     -.359
POISEUILLE VISCOSITY CAP 1 (GM/CM SEC)      .111209E-03      .762
POISEUILLE VISCOSITY CAP 2 (GM/CM SEC)      .121289E-03     9.895

MAX VISCOSITY ERROR ( +OR- PERCENT )               .396      .432     1.487

MASS FLOW RATE (GM/SEC)                     .123639E-02
DENSITY OF N2 IN VOLUMETER (GM/CC)          .118495E-02
DENSITY OF N2 IN CAP 1 (GM/CC)              .267227E-02            CAP 2             .264103E-02
MEAN PRESSURE IN CAP 1 (GM/SQ CM)           .126183E+04            CAP 2             .125178E+04
PRESSURE DROP ACROSS CAP 1 (GM/SQ CM)       .181675E+02            CAP 2             .193000E+01
RATIO OF PRESSURE DROPS  CAP1/CAP2             9.413209
REYNOLDS NUMBER                               .2857E+03
ENTRANCE LENGTH (CM)                          .9292E+00
GAS VELOCITY (CM/SEC)                         .2353E+03

DATA PRINT OUT
               162.26         162.85         298.92         299.12
    35       -3.64800       -3.63200        1.02100        1.02900
    35       98.66700       96.30500       74.07100       17.60000       29.90000        5.00000      768.56
    35              1
```

SAMPLE OUTPUT

```
      PROGRAM TST (INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,
     1TAPE7=PUNCH)
C
C
      DIMENSION VV(340),TT(340),VOLT(4),T(4)
      COMMON/AIR/C(4,6)
C
C     THERMOCOUPLE TABLES TEMP=TT  VOLTAGE=VV
C
      DATA (VV(I),I=1,35)/-5.537,-5.522,-5.507,-5.492,-5.477,
     1-5.460,-5.443,-5.427,-5.411,-5.395,
     1-5.379,-5.362,-5.345,-5.328,-5.311,
     1-5.294,-5.276,-5.258,-5.241,-5.223,
     1-5.205,-5.187,-5.169,-5.150,-5.132,
     1-5.113,-5.094,-5.075,-5.056,-5.037,
     1-5.018,-4.998,-4.978,-4.959,-4.939/
C
C
      DATA (VV(I),I=36,70)/-4.919,-4.899,-4.878,-4.858,-4.838,
     1-4.817,-4.796,-4.775,-4.754,-4.733,
     1-4.712,-4.690,-4.669,-4.647,-4.625,
     1-4.603,-4.581,-4.559,-4.537,-4.514,
     1-4.492,-4.469,-4.446,-4.423,-4.400,
     1-4.377,-4.354,-4.330,-4.307,-4.283,
     1-4.259,-4.235,-4.211,-4.187,-4.162/
C
C
      DATA (VV(I),I=71,105)/-4.138,-4.114,-4.089,-4.064,-4.039,
     1-4.014,-3.989,-3.964,-3.938,-3.912,
     1-3.887,-3.861,-3.835,-3.809,-3.783,
     1-3.757,-3.730,-3.704,-3.678,-3.651,
     1-3.624,-3.597,-3.570,-3.542,-3.515,
     1-3.488,-3.460,-3.432,-3.405,-3.377,
     1-3.349,-3.320,-3.292,-3.264,-3.235/
C
C
      DATA (VV(I),I=106,140)/-3.207,-3.178,-3.149,-3.120,-3.091,
     1-3.062,-3.033,-3.003,-2.974,-2.944,
     1-2.914,-2.884,-2.854,-2.824,-2.794,
     1-2.764,-2.733,-2.703,-2.672,-2.642,
     1-2.611,-2.580,-2.549,-2.518,-2.486,
     1-2.455,-2.423,-2.392,-2.360,-2.328,
     1-2.296,-2.264,-2.232,-2.200,-2.167/
C
C
      DATA (VV(I),I=141,175)/-2.135,-2.103,-2.070,-2.037,-2.004,
     1-1.971,-1.938,-1.905,-1.871,-1.838,
     1-1.804,-1.771,-1.737,-1.703,-1.669,
     1-1.635,-1.601,-1.567,-1.532,-1.498,
     1-1.463,-1.429,-1.394,-1.359,-1.324,
     1-1.289,-1.254,-1.218,-1.183,-1.148,
     1-1.112,-1.067,-1.041,-1.005,-0.969/
C
C
      DATA (VV(I),I=176,210)/-0.933,-0.897,-0.860,-0.842,-0.788,
```

MAIN PROGRAM LISTING

```
     1-0.751,-0.714,-0.678,-0.641,-0.604,
     1-0.567,-0.530,-0.492,-0.455,-0.417,
     1-0.380,-0.343,-0.305,-0.267,-0.229,
     1-0.191,-0.153,-0.115,-0.077,-0.038,
     10.000,0.038,0.077,0.116,0.154,
     10.193,0.232,0.271,0.311,0.350/
C
C
      DATA (VV(I),I=211,245)/0.389,0.429,0.468,0.508,0.547,
     10.587,0.627,0.667,0.707,0.747,
     10.787,0.827,0.868,0.908,0.949,
     10.990,1.030,1.071,1.112,1.153,
     11.194,1.235,1.277,1.318,1.360,
     11.401,1.443,1.485,1.526,1.568,
     11.610,1.652,1.694,1.737,1.779/
C
C
      DATA (VV(I),I=246,280)/1.821,1.864,1.907,1.949,1.992,
     12.035,2.078,2.121,2.164,2.207,
     12.250,2.293,2.336,2.380,2.423,
     12.467,2.511,2.555,2.599,2.643,
     12.687,2.731,2.775,2.820,2.864,
     12.908,2.953,2.997,3.042,3.087,
     13.132,3.177,3.222,3.267,3.312/
C
C
      DATA (VV(I),I=281,315)/3.357,3.402,3.448,3.493,3.539,
     13.584,3.630,3.676,3.722,3.767,
     13.813,3.859,3.906,3.952,3.998,
     14.044,4.091,4.138,4.184,4.230,
     14.277,4.324,4.371,4.418,4.465,
     14.521,4.559,4.606,4.654,4.701,
     14.749,4.796,4.843,4.891,4.939/
C
C
      DATA (VV(I),I=316,340)/4.987,5.035,5.083,5.131,5.179,
     15.227,5.275,5.323,5.372,5.420,
     15.469,5.518,5.566,5.615,5.663,
     15.712,5.761,5.810,5.859,5.908,
     15.957,6.007,6.056,6.105,6.155/
C
C
      TT(1)=-200.0
      DO 200 N=2,340
      TT(N)=TT(N-1)+1
  200 CONTINUE
C
C     CHECK GENERATED TABLES
C
      DO 250 N=1,340
      TK=TT(N)+273.15
      WRITE(6,225)TT(N),TK,VV(N)
  225 FORMAT(1H ,3F10.3)
  250 CONTINUE
C
```

```
C
      DO 255 I=1,4
      READ(5,253)(C(I,J),J=1,6)
  253 FORMAT(6F10)
  255 CONTINUE
C
C     NUMBER OF RUNS TO BE CALCULATED
C
      READ(5,260)NRUNS
  260 FORMAT(I5)
C
C     THERMOCOUPLE READINGS  4--5--8--9   (MV)
C
  275 READ(5,300)NUM1,(VOLT(N),N=1,4)
  300 FORMAT(I5,4F10.5)
C
C     COLUMN LENGTHS (CM OIL) ,PRESSURE(PSIG) ,ATMOSPHRIC PRESSURE (CM HG)
C     VOLUMETER DIFF PRESS (CM OIL) , VOLUMETER TIME (SEC)
C
      READ(5,310)NUM2,COL1,COL2,COL3,PIN,PAHG,DP8,TIME
  310 FORMAT(I5,7F10.5)
C
C     VOLUMETER LENGH USED
C
      READ(5,330)NUM4,IVOL
  330 FORMAT(2I5)
C
C     DEFINE TEMPERATURES  4--5--8--9
C
      DO 600 N=1,4
      DO 500 I=1,340
      IF(VOLT(N).LT.VV(I))GO TO 510
  500 CONTINUE
  510 II=I-1
      DV=VV(I)-VV(II)
      DPV=VOLT(N)-VV(II)
      DT=TT(I)-TT(II)
      T(N)=TT(II)+DT*DPV/DV
  600 CONTINUE
C
C     VARIABLES NOW DEFINED
C     CONVERT TEMP TO DEGREES K
C
      T4=T(1)+273.15
      T5=T(2)+273.15
      T8=T(3)+273.15
      T9=T(4)+273.15
C
C     ATMOSPHERIC PRESSURE (GM/SQ CM)
C
      PATM=PAHG*13.5955*2.54
C
C     MEAN CHAMBRE PRESSURE (GN/SQ CM)
C
      PM=PIN*70.307+PATM
```

```
      IF(PIN.LT.20.)PM=PIN*13.545+PATM
C
C     MEAN GAS DENSITY IN MONOMETER (GM/CC)
C
C
      PAM=PM/1033.2
      CALL DENS(T9,PAM,RMON)
C
C     OIL COMPRESSIBILITY CORRECTION (GM/GM/ATM)
C
      COMS=0.6108E-4
C
C     PRESSURE LOSS ACROSS CAPILIARIES 1 AND 2 (GM/SQ CM)
C
      SPGOIL=0.8210*(1.+PAM*COMS)
      RWAT=0.998203-.00021*(T9-293.15)
      DDENS=SPGOIL*RWAT-RMON
      DP1=(COL2-COL3)*DDENS
      DP2=(COL1-COL2)*DDENS
C
C     MEAN CAPILIARY PRESSURES 1 AND 2 (GM/SQ CM)
C
      PAV1=PM-DP1/2.0
      PAV2=PM-DP1-DP2/2.0
C
C     MEAN CHAMBRE TEMPERATURE (DEG K)
C
      TAV=T4
C
C     GAS DENSITY CAPS 1AND 2  (GM/CC)    R1 ,R2
C
      PA1=PAV1/1033.2
      PA2=PAV2/1033.2
      CALL DENS(T4,PA1,R1)
      CALL DENS(T5,PA2,R2)
C
C................................................................
C
C
C
C     VOLUMETER GAS DENSITY (GM/CC)
C
      PVOL=PATM+DPB*0.81944
      PPVV=PVOL/1033.2
      CALL DENS(T8,PPVV,RV)
C
C     MASS FLOW RATE (GM/SEC)    Q
C
      IF(IVOL.EQ.1)VOL=801.924
      IF(IVOL.EQ.2)VOL=401.210
      IF(IVOL.EQ.3)VOL=200.288
      Q=VOL*RV/TIME
C
C     CAPIL CALIB TEMP CORRECTION
C
```

```
      DELT=TAV-297.15
C
C     VISCOSITY CALCULATION
C
      PI=3.1415926536
      G=980.3941
      ALF=3.3E-06
C
C     DEFINE CAPILLARIES USED
C
      IF(NUM1.GE.30)GO TO 608
      AL1=51.817
      AL2=5.967
      D1=0.03061979
      D2=0.03048573
      GO TO 610
  608 CONTINUE
      AL1=53.162
      AL2=5.161
      D1=0.0500312
      D2=0.0501366
  610 CONTINUE
C
C
      AA=PI*(D1**4)*G*(1.0+3.0*ALF*DELT)
      BB=128.0*Q*(AL1-AL2)
      CC=DP1*R1-(((D2/D1)**4)*DP2*R2)
      VISC=AA*CC/BB
      PRES=(PA1+PA2)/2.0
C
C     CALCULATE VISCOSITIES FOR ONE AND TWO SEPARATELY
C
      AAL=PI*(D1**4)*R1*G*DP1*(1.+3.*ALF*DELT)
      BBL=128.0*Q*(AL1+0.6*D1)
      CCL=1.12*Q/(8.0*PI*(AL1+0.6*D1))
      VISCL=(AAL/BBL)-CCL
      VISPL=AAL/(128.0*Q*AL1)
      AAS=PI*(D2**4)*R2*G*DP2*(1.+3.*ALF*DELT)
      BBS=128.0*Q*(AL2+0.6*D2)
      CCS=1.12*Q/(8.0*PI*(AL2+0.6*D2))
      VISCS=(AAS/BBS)-CCS
      VISPS=AAS/(128.0*Q*AL2)
      RATI=DP1/DP2
C
C     MAXIMUM ERROR LIMITS
C
      BER=(D1**4)*DP1*R1
      CER=(D2**4)*DP2*R2
      AH1=COL2-COL3
      AH2=COL1-COL2
      C1=420.9E-8
      C2=306.4E-8
      DBOB=SQRT(C1+(.006/AH1)**2+(.3/TAV)**2)
      DCOC=SQRT(C1+(.006/AH2)**2+(.3/TAV)**2)
      DB=DBOB*BER
```

```
      DC=DCOC*CER
      DDP=(DB+DC)/(BER-CER)
      DVOV=100.0*(SQRT(C2+DDP**2))
      XX1=AAL/BBL
      C3=727.62E-8
      DX1=XX1*(SQRT(C3+(0.3/TAV)**2+(.006/AH1)**2))
      DY1=.107*CCL
      DVL=100.0*((DX1+DY1)/VISCL)
      XX2=AAS/BBS
      C4=729.9E-8
      DX2=XX2*(SQRT(C4+(0.3/TAV)**2+(.006/AH2)**2))
      DY2=.107*CCS
      DVS=100.0*((DX2+DY2)/VISCS)
C
C      CALCULATE PERCENT DEVIATION FROM RECOMMENDED VALUE
C
      IF(TAV.LT.240)GO TO 620
      VTHEO=(4.0201+0.74582*TAV-5.7171E-4*TAV**2+2.9928E-7*TAV**3
     1-6.2524E-11*TAV**4)*1.0E-6
      DVDT=(0.74582-2.0*5.71710E-4*TAV+3.0*2.9928E-7*TAV**2-4.0*
     16.2524E-11*TAV**3)*1.0E-6
      GO TO 650
  620 CONTINUE
      VTHEO=(-6.677+0.85155*TAV-8.9470E-4*TAV**2+5.6831E-7*TAV**3)
     1*1.0E-6
      DVDT=(0.85155-2.0*8.9470E-4*TAV+3.0*5.6831E-7*TAV**2)*1.0E-6
  650 PCTPD=DVDT*100.0/VTHEO
      DVISC=(VISC-VTHEO)*100.0/VTHEO
      DVISCL=(VISCL-VTHEO)*100./VTHEO
      DVISCS=(VISCS-VTHEO)*100./VTHEO
      DVISPL=(VISPL-VTHEO)*100./VTHEO
      DVISPS=(VISPS-VTHEO)*100./VTHEO
C
C     REYNOLDS NUMBER AND ENTRANCE LENGTH ( 1 PERCENT )
C
      RE=4.0*Q/(PI*D1*VISC)
      XENT=0.065*RE*D1
C
C      GAS VELOCITY IN CAPILIARIES (CM/SEC)
C
      VCTY=RE*VISC/(R1*D1)
C
C     PUNCH OUTPUT
C
      NSS=100+NUM1
      WRITE(7,901)NSS,VISC,TAV,PRES,R1
  901 FORMAT(I5,4E18.9)
C
C     PRINT OUT RESULTS
C
      WRITE(6,700)NUM1
      WRITE(6,705)VTHEO,DVDT,PCTPD
      WRITE(6,710)VISC,DVISC
      WRITE(6,720)TAV
      WRITE(6,730)PRES
```

```
      WRITE(6,740)VISCL,DVISCL
      WRITE(6,741)VISCS,DVISCS
      WRITE(6,745)VISPL,DVISPL
      WRITE(6,746)VISPS,DVISPS
      WRITE(6,751)DVOV,DVL,DVS
      WRITE(6,760)Q
      WRITE(6,770)RV
      WRITE(6,780)R1,R2
      WRITE(6,790)PAV1,PAV2
      WRITE(6,800)DP1,DP2
      WRITE(6,820)RATI
      WRITE(6,822)RE
      WRITE(6,825)XENT
      WRITE(6,827)VCTY
      WRITE(6,830)
      WRITE(6,840)T4,T5,T8,T9
  700 FORMAT(1H1,11HRUN NUMBER ,I3)
  705 FORMAT(1H0,/,32H RECOMMENDED VALUE OF VISCOSITY ,E23.6,12X,11H(DVI
     1SC/DT) ,E18.6,F10.3)
  710 FORMAT(1H0,22HVISCOSITY (GM/CM SEC) ,E32.6,F10.3)
  720 FORMAT(1H0,21HTEMPERATURE (DEG. K) ,F33.6)
  730 FORMAT(1H0,15HPRESSURE (ATM) ,F39.6)
  740 FORMAT(1H0,/,40H VISCOSITY USING ONLY CAP 1 (GM/CM SEC) ,E15.6,
     1F10.3)
  741 FORMAT(1H0,39HVISCOSITY USING ONLY CAP 2 (GM/CM SEC) ,E15.6,F10.3)
  745 FORMAT(1H0,39HPOISEUILLE VISCOSITY CAP 1 (GM/CM SEC) ,E15.6,F10.3)
  746 FORMAT(1H0,39HPOISEUILLE VISCOSITY CAP 2 (GM/CM SEC) ,E15.6,F10.3)
  751 FORMAT(1H0,/,38H MAX VISCOSITY ERROR ( +OR- PERCENT ) ,F17.3,
     12F10.3)
  760 FORMAT(1H0,/,25H MASS FLOW RATE (GM/SEC) ,E30.6)
  770 FORMAT(1H0,35HDENSITY OF N2 IN VOLUMETER (GM/CC) ,E19.6)
  780 FORMAT(1H0,31HDENSITY OF N2 IN CAP 1 (GM/CC) ,E23.6,12X,5HCAP 2,
     1E24.6)
  790 FORMAT(1H0,34HMEAN PRESSURE IN CAP 1 (GM/SQ CM) ,E20.6,12X,5HCAP 2
     1,E24.6)
  800 FORMAT(1H0,38HPRESSURE DROP ACROSS CAP 1 (GM/SQ CM) ,E16.6,12X,
     15HCAP 2,E24.6)
  820 FORMAT(1H0,36HRATIO OF PRESSURE DROPS  CAP1/CAP2  ,F18.6)
  822 FORMAT(1H0,16HREYNOLDS NUMBER ,E38.4)
  825 FORMAT(1H0,21HENTRANCE LENGTH (CM) ,E33.4)
  827 FORMAT(1H0,22HGAS VELOCITY (CM/SEC) ,E32.4)
  830 FORMAT(1H0,/,16H DATA PRINT OUT )
  840 FORMAT(1H0,F20.2,3F15.2)
C
C     LIST DATA
C
      WRITE(6,110)NUM1,(VOLT(N),N=1,4)
  110 FORMAT(1H0,I5,4F15.5)
      WRITE(6,120)NUM2,COL1,COL2,COL3,PIN,PAHG,DPB,TIME
  120 FORMAT(1H0,I5,7F15.5)
      WRITE(6,140)NUM4,IVOL
  140 FORMAT(1H0,I5,I15)
      IF(NUM1.LT.NRUNS)GO TO 275
      STOP
      END
```

APPENDIX A2

GAS DENSITY COMPUTATION

The density of the gases were calculated using a computer subroutine of the form DENS(T,P,ρ) where temperature, T, and pressure, P, are input arguments and the density, ρ, is an output argument.

NITROGEN DENSITY

In the case of nitrogen gas an equation of state obtained from reference [20] was used, that is:

$$\begin{aligned} P = {} & \rho RT + (n_1T + n_2 + n_3.T^2 + n_4/T^4)\ \rho^2 \\ & + (n_5T^2 + n_6T + n_7 + n_8/T + n_9/T^2)\ \rho^2 \\ & + (n_{10}T + n_{11})\ \rho^4 + (n_{12} + n_{13}/T)\ \rho^5 \\ & + (n_{14}/T^2 + n_{15}/T^3 + n_{16}/T^4)\ \rho^3\ \mathrm{EXP}(n_{23}\ \rho^2) \\ & + (n_{17}/T^2 + n_{18}/T^3 + n_{19}/T^4)\ \rho^5\ \mathrm{EXP}(n_{23}\ \rho^2) \\ & + (n_{20}/T^2 + n_{21}/T^3 + n_{22}/T^4)\ \rho^7\ \mathrm{EXP}(n_{23}\ \rho^2) \qquad \text{(A2.1)} \end{aligned}$$

The subroutine started with an initial estimate of density in the form $\rho = P/RT$, then calculated a value of P using equation (A2.1). It then corrected the initial value of density using $\rho_i = \rho_{i-1} \times P_{ACTUAL}/P_{CALC}$. This iterative procedure continued until convergence, defined by $\rho_i - \rho_{i-1} \rightarrow 0$, was achieved .

The programme is listed at the end of this section.

AIR DENSITY

The density of air was calculated in a similar manner, to that of nitrogen, using the equation of state obtained form reference [21] that was of the form:

$$\rho = P/ZRT$$

$$Z = \alpha_o/T^* + \alpha_1 + B/T^{*2} + \gamma/T^{*3}$$

where

$$\alpha_o = n_1\omega + n_2\omega^2 + n_3\omega^3 + n_4\omega^4 + n_5\omega^5 + n_6\omega^8$$

$$\alpha_1 = 1 + n_7\omega + n_8\omega^2 + n_9\omega^3 + n_{10}\omega^4 + n_{11}\omega^6 + n_{12}\omega^8$$

$$B_2 = n_{13}\omega + n_{14}\omega^2 + n_{15}\omega^3 + n_{16}\omega^4 + n_{17}\omega^6 + n_{18}\omega^8$$

$$\gamma = n_{19}\omega + n_{20}\omega^2 + n_{21}\omega^3 + n_{22}\omega^4 + n_{23}\omega^6 + n_{24}\omega^8 \qquad \text{(A2.2)}$$

In the above equation T* is the reduced temperature, i.e. T/T_{CRIT}, and ω the reduced density, i.e. ρ/ρ_{CRIT}. The critical constants are given as $T_{CRIT} = 132.55°K$ and $\rho_{CRIT} = 0.3128617464 \text{ gm/cm}^3$.

The ideal gas density was first calculated from the equation $\rho_{IDL} = P/RT$, this value of density was then used to compute a value of Z from equation(A2.2) after which a new value of density was computed using $\rho = \rho_{IDL}/Z$. Each new value of density was then used to calculate a new value of Z and the iterative procedure continued until convergence occurred.

A listing of this subroutine is also presented at the end of this section.

```
      SUBROUTINE DENS(T,P,RO1)
      X1=3.737629158E-3
      X2=-1.172097206
      X3=-6.739128906E3
      X4=1.377006800E7
      X5=6.685763765E-8
      X6=-4.380718747E-5
      X7=8.457392454E-2
      X8=-5.706317902
      X9=4.431848145E2
      X10=5.934089131E-6
      X11=-4.195030779E-3
      X12=1.336665009E-4
      X13=-2.295834478E-3
      X14=-4.089562500E3
      X15=9.267618125E5
      X16=-5.631292800E7
      X17=1.032092381E1
      X18=-2.712277588E3
      X19=2.244106875E5
      X20=-3.343751654E-2
      X21=6.719458580
      X22=-4.595295410E2
      X23=-0.0056
      RU=0.08205615593
      N=0
      R=P/(RU*T)
   50 N=N+1
      PN=R*RU*T+(X1*T+X2+X3/T**2+X4/T**4)*R**2
     1+(X5*T**2+X6*T+X7+X8/T+X9/T**2)*R**3+(X10*T+X11)*R**4
     1+(X12+X13/T)*R**5
     1+((X14/T**2+X15/T**3+X16/T**4)*R**3)*(EXP(X23*R**2))
     1+((X17/T**2+X18/T**3+X19/T**4)*R**5)*(EXP(X23*R**2))
     1+((X20/T**2+X21/T**3+X22/T**4)*R**7)*(EXP(X23*R**2))
      ROLD=R
      R=R*P/PN
      RO1=R*0.0280134
      YY=ABS((R-ROLD)/R)
      IF(YY.LT.0.0001)GO TO 99
      IF(N.GT.100)GO TO 99
      GO TO 50
   99 RETURN
      END
```

NITROGEN DENSITY PROGRAM

```
      SUBROUTINE DENS(T,P,ROW)
C
C
      COMMON/AIR/C(4,6)
      DIMENSION A(4)
C
C
      RCR=0.3128617464
      RU=2.8333899
      N=0
      RIDL=P/(RCR*RU*T)
      R=RIDL
      TAU=T/132.55
C
C
    1 N=N+1
C
C
      DO 100 I=1,4
      SUM=0.0
C
C
      DO 90 J=1,6
      K=J
      IF(J.EQ.5)K=6
      IF(J.EQ.6)K=8
      SUM=SUM+C(I,J)*R**K
   90 CONTINUE
C
C
      A(I)=SUM
  100 CONTINUE
C
C
      ZZ=1.0+A(1)/TAU+A(2)+A(3)/TAU**2+A(4)/TAU**3
C
C
      ROLD=R
      R=RIDL/ZZ
      ROW=R*RCR
C
C
      YY=ABS((R-ROLD)/R)
      IF(YY.LT.0.00001)RETURN
      IF(N.EQ.20)RETURN
      GO TO 1
      END
```

AIR DENSITY PROGRAM

APPENDIX A3

VISCOSITY DATA OF OTHER AUTHORS

TABLE A3.1 NITROGEN VISCOSITY DATA
OTHER AUTHORS

VOGEL (1914)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.56000E-04	81.600
.16780E-03	273.150

VASILESCO (1945)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.61550E-04	90.200
.12600E-03	194.760
~~.16637E-03~~	~~273.100~~

CLARK AND SMITH (1968)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.76600E-04	114.350
.90000E-04	134.400
~~.10120E-03~~	~~152.500~~
.11540E-03	176.000
.12960E-03	200.900
.14310E-03	225.700
~~.15620E-03~~	~~252.300~~
.16610E-03	272.450
.17860E-03	299.100
.18960E-03	322.700
~~.19920E-03~~	~~344.800~~
.21210E-03	374.600

TRAUTZ AND BAUMANN (1929)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.12730E-03	195.650
.12750E-03	196.850
~~.14640E-03~~	~~232.750~~
.14650E-03	235.250
.17280E-03	289.250
.17350E-03	290.950
~~.18800E-03~~	~~324.200~~
.20840E-03	373.200

JOHNSTON AND MC CLOSKEY (1940)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.63140E-04	90.170
.81640E-04	118.260
~~.89240E-04~~	~~130.820~~
.95470E-04	140.980
.10418E-03	155.560
.11225E-03	169.400
~~.12100E-03~~	~~184.720~~
.12982E-03	200.160
.13808E-03	215.750
.14535E-03	229.880
~~.15313E-03~~	~~245.190~~
.16030E-03	260.130
.16650E-03	273.210
.17195E-03	285.080
~~.17849E-03~~	~~300.050~~

MICHELS AND GIBSON (1931)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.17940E-03	298.150	10.950	.12564E-01
.17960E-03	298.150	12.710	.14587E-01
.17990E-03	298.150	13.570	.15576E-01
.18030E-03	298.150	14.440	.16577E-01
.18020E-03	298.150	15.330	.17601E-01
.18050E-03	298.150	15.350	.17635E-01
.18640E-03	298.150	48.220	.55437E-01
.18840E-03	298.150	57.590	.66168E-01
.19080E-03	298.150	66.980	.76873E-01
.19810E-03	298.150	92.310	.10541E+00
.20050E-03	298.150	104.500	.11892E+00
.20490E-03	298.150	118.600	.13430E+00
.20940E-03	298.150	132.700	.14940E+00
.21990E-03	298.150	165.500	.18324E+00
.22310E-03	298.150	174.900	.19257E+00
.22820E-03	298.150	189.000	.20624E+00
.23670E-03	298.150	212.400	.22803E+00
.25830E-03	298.150	277.700	.28293E+00
.27640E-03	298.150	320.400	.31438E+00
.29410E-03	298.150	364.600	.34366E+00
.29430E-03	298.150	364.600	.34366E+00
.30400E-03	298.150	387.600	.35774E+00
.31940E-03	298.150	430.200	.38196E+00
.32090E-03	298.150	430.200	.38196E+00
.33740E-03	298.150	473.100	.40412E+00
.33850E-03	298.150	476.100	.40562E+00
.19130E-03	323.150	15.370	.16238E-01
.19810E-03	323.150	57.600	.60525E-01
.20880E-03	323.150	104.500	.10827E+00
.23730E-03	323.150	212.400	.20756E+00
.27370E-03	323.150	320.400	.28855E+00
.31230E-03	323.150	430.200	.35395E+00
.20220E-03	348.150	15.370	.15043E-01

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.20830E-03	348.150	57.610	.55846E-01
~~.21750E-03~~	~~348.150~~	~~104.500~~	~~.99584E-01~~
.24080E-03	348.150	212.400	.19089E+00
.27460E-03	348.150	320.300	.26692E+00
.30730E-03	348.150	430.200	.32992E+00
~~.34250E-03~~	~~348.150~~	~~541.700~~	~~.38222E+00~~

ROSS AND BROWN (1957)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.18500E-03	298.150	35.010	.40256E-01
.18600E-03	298.150	46.970	.54003E-01
~~.19030E-03~~	~~298.150~~	~~69.030~~	~~.79203E-01~~
.20080E-03	298.150	103.040	.11731E+00
.20850E-03	298.150	137.050	.15400E+00
.23230E-03	298.150	205.080	.22134E+00
~~.25640E-03~~	~~298.150~~	~~273.100~~	~~.27934E+00~~
.28600E-03	298.150	341.140	.32850E+00
.31030E-03	298.150	409.160	.37029E+00
.17270E-03	273.150	35.010	.44307E-01
~~.18250E-03~~	~~273.150~~	~~69.030~~	~~.87755E-01~~
.19010E-03	273.150	103.040	.13060E+00
.20350E-03	273.150	137.050	.17186E+00
.23080E-03	273.150	205.080	.24657E+00
~~.26040E-03~~	~~273.150~~	~~273.100~~	~~.30899E+00~~
.29230E-03	273.150	341.140	.36041E+00
.16190E-03	248.050	35.010	.49403E-01
.17330E-03	248.050	69.030	.98889E-01
~~.18180E-03~~	~~248.050~~	~~103.040~~	~~.14830E+00~~
.19710E-03	248.050	137.050	.19586E+00
.23130E-03	248.050	205.080	.27974E+00
.26270E-03	248.050	273.100	.34658E+00

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
~~.29810E-03~~	~~248.050~~	~~341.140~~	~~.39953E+00~~
.15270E-03	223.350	35.010	.55926E-01
.16710E-03	223.350	69.030	.11392E+00
.17630E-03	223.350	103.040	.17302E+00
~~.19340E-03~~	~~223.350~~	~~137.030~~	~~.22946E+00~~
.23290E-03	223.350	205.080	.32401E+00
.27120E-03	223.350	273.100	.39408E+00

KESTIN AND WANG (1958)

~~VISCOSITY~~ (POISE)	~~TEMPERATURE~~ (DEG K)	~~PRESSURE~~ (ATMOS)	~~DENSITY~~ (GM/CC)
.17800E-03	298.150	2.000	.22911E-02
.17840E-03	298.150	5.000	.57311E-02
~~.17930E-03~~	~~298.150~~	~~10.000~~	~~.11472E-01~~
.18090E-03	298.150	20.000	.22975E-01
.18260E-03	298.150	30.000	.34489E-01
.18460E-03	298.150	40.000	.45996E-01
~~.18670E-03~~	~~298.150~~	~~50.000~~	~~.57479E-01~~
.18990E-03	298.150	60.000	.68920E-01
.19160E-03	298.150	70.000	.80304E-01
.19460E-03	298.150	80.000	.91614E-01
~~.19730E-03~~	~~298.150~~	~~90.000~~	~~.10284E+00~~
.20150E-03	298.150	100.000	.11395E+00

KESTIN AND LEIDENFROST (1960)

~~VISCOSITY~~ (POISE)	~~TEMPERATURE~~ (DEG K)	~~PRESSURE~~ (ATMOS)	~~DENSITY~~ (GM/CC)
.18779E-03	293.150	62.070	.72667E-01
.18438E-03	293.150	48.630	.57040E-01
~~.18124E-03~~	~~293.150~~	~~34.820~~	~~.46778E-01~~

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.17864E-03	293.150	20.480	.23949E-01
.17814E-03	293.150	18.040	.21088E-01
.17758E-03	293.150	14.590	.17046E-01
~~.17696E-03~~	~~293.150~~	~~11.170~~	~~.13042E-01~~
.17650E-03	293.150	7.790	.90890E-02
.19164E-03	298.150	69.040	.79214E-01
.18801E-03	298.150	55.500	.63778E-01
~~.18479E-03~~	~~298.150~~	~~41.850~~	~~.48134E-01~~
.18212E-03	298.150	28.210	.32428E-01
.17989E-03	298.150	14.600	.16761E-01
.17833E-03	298.150	7.800	.89450E-02

WHITELAW (1960)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.17350E-03	289.150	9.630	.11459E-01
.17450E-03	289.150	19.360	.22965E-01
~~.18200E-03~~	~~295.650~~	~~19.350~~	~~.22435E-01~~
.17600E-03	290.150	20.330	.24032E-01
.17680E-03	290.650	20.330	.23989E-01
.18210E-03	292.150	39.680	.46655E-01
~~.18240E-03~~	~~288.150~~	~~57.100~~	~~.68192E-01~~
.18530E-03	290.150	64.850	.76805E-01
.19600E-03	292.150	87.110	.10202E+00
.19700E-03	292.150	90.980	.10646E+00
~~.19800E-03~~	~~292.150~~	~~93.880~~	~~.10978E+00~~
.19730E-03	290.350	96.790	.11394E+00
.19830E-03	290.350	96.790	.11394E+00
.20860E-03	296.150	113.240	.12953E+00

FLYNN , HANKS , LEMAIRE AND ROSS (1963)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.21327E-03	373.150	26.350	.23962E-01
.21634E-03	373.150	53.140	.47928E-01
~~.22135E-03~~	~~373.150~~	~~80.540~~	~~.71897E-01~~
.22698E-03	373.150	108.670	.95829E-01
.23306E-03	373.150	137.750	.11977E+00
.23958E-03	373.150	168.020	.14372E+00
~~.17812E-03~~	~~298.150~~	~~6.770~~	~~.77624E-02~~
.18028E-03	298.150	20.860	.23965E-01
.18393E-03	298.150	41.670	.47916E-01
.18634E-03	298.150	52.200	.60000E-01
~~.18868E-03~~	~~298.150~~	~~62.580~~	~~.71864E-01~~
.19422E-03	298.150	83.720	.95800E-01
.20051E-03	298.150	105.250	.11974E+00
.20729E-03	298.150	127.340	.14370E+00
~~.21503E-03~~	~~298.150~~	~~150.130~~	~~.16767E+00~~
.22275E-03	298.150	173.970	.19166E+00
.16072E-03	248.150	33.930	.47827E-01
.16538E-03	248.150	50.470	.71758E-01
~~.17661E-03~~	~~248.150~~	~~83.400~~	~~.11981E+00~~
.19049E-03	248.150	117.010	.16807E+00
.20723E-03	248.150	152.540	.21631E+00
.21714E-03	248.150	171.500	.24035E+00
~~.14849E-03~~	~~223.150~~	~~29.930~~	~~.47683E-01~~
.15867E-03	223.150	58.250	.95386E-01
.17136E-03	223.150	85.930	.14356E+00
.18693E-03	223.150	114.050	.19206E+00
~~.20536E-03~~	~~223.150~~	~~143.730~~	~~.24035E+00~~
.22699E-03	223.150	176.580	.28809E+00
.13850E-03	194.650	37.110	.71035E-01
.14940E-03	194.650	59.150	.11884E+00
~~.16990E-03~~	~~194.650~~	~~90.830~~	~~.19237E+00~~
.20040E-03	194.650	123.020	.26438E+00
.22470E-03	194.650	147.130	.31134E+00
.25350E-03	194.650	174.190	.35595E+00

GOLDMAN (1963)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.19230E-03	298.200	77.600	.88890E-01
.20440E-03	298.200	119.700	.13546E+00
~~.19940E-03~~	~~298.200~~	~~101.900~~	~~.11603E+00~~
.17140E-03	211.900	88.700	.16105E+00
.16430E-03	211.900	76.400	.13728E+00
.15120E-03	211.900	51.400	.89699E-01
~~.18830E-03~~	~~211.900~~	~~117.600~~	~~.21586E+00~~
.17720E-03	211.900	99.100	.18107E+00
.16350E-03	194.700	77.000	.15987E+00
.16040E-03	194.700	75.000	.15520E+00
~~.14630E-03~~	~~194.700~~	~~52.600~~	~~.10419E+00~~
.14410E-03	194.700	51.000	.10067E+00
.20840E-03	194.700	123.900	.26608E+00
.21240E-03	194.700	125.500	.26939E+00
~~.18440E-03~~	~~194.700~~	~~101.700~~	~~.21742E+00~~
.18070E-03	194.700	100.000	.21353E+00

KESTIN AND WHITELAW (1963)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.22748E-03	348.060	138.250	.12972E+00
.22553E-03	345.280	134.710	.12777E+00
~~.21964E-03~~	~~345.220~~	~~110.350~~	~~.10588E+00~~
.21356E-03	344.970	82.930	.80516E-01
.20883E-03	344.750	55.370	.54277E-01
.20417E-03	344.510	28.290	.27929E-01
~~.19844E-03~~	~~344.310~~		
.23280E-03	372.230	131.850	.11528E+00
.22830E-03	372.160	109.870	.97111E-01
.22390E-03	372.150	82.320	.73644E-01
~~.22020E-03~~	~~372.140~~	~~55.710~~	~~.50345E-01~~
.21521E-03	372.100	27.670	.25227E-01
.21022E-03	372.100		

KAO AND KOBAYASHI (1967)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.18958E-03	323.150	10.000	.10566E-01
.19116E-03	323.150	20.000	.21125E-01
~~.19399E-03~~	~~323.150~~	~~40.000~~	~~.42165E-01~~
.19772E-03	323.150	60.000	.63014E-01
.20236E-03	323.150	80.000	.83580E-01
.21158E-03	323.150	120.000	.12354E+00
~~.23512E-03~~	~~323.150~~	~~200.000~~	~~.19706E+00~~
.26779E-03	323.150	300.000	.27465E+00
.30274E-03	323.150	400.000	.33741E+00
.33860E-03	323.150	500.000	.38860E+00
~~.17020E-03~~	~~273.150~~	~~20.000~~	~~.25201E-01~~
.17246E-03	273.150	40.000	.50679E-01
.17756E-03	273.150	60.000	.76240E-01
.18358E-03	273.150	80.000	.10169E+00
~~.19756E-03~~	~~273.150~~	~~120.000~~	~~.15143E+00~~
.23056E-03	273.150	200.000	.24141E+00
.27563E-03	273.150	300.000	.33050E+00
.32340E-03	273.150	400.000	.39778E+00
~~.14229E-03~~	~~223.150~~	~~10.000~~	~~.15508E-01~~
.14471E-03	223.150	20.000	.31418E-01
.15055E-03	223.150	40.000	.64321E-01
.15858E-03	223.150	60.000	.98405E-01
~~.16785E-03~~	~~223.150~~	~~80.000~~	~~.13320E+00~~
.19005E-03	223.150	120.000	.20203E+00
.24152E-03	223.150	200.000	.31829E+00
.11904E-03	183.150	10.000	.19210E-01
~~.12284E-03~~	~~183.150~~	~~20.000~~	~~.39611E-01~~
.13230E-03	183.150	40.000	.84294E-01
.14558E-03	183.150	60.000	.13440E+00
.16167E-03	183.150	80.000	.18876E+00
~~.20656E-03~~	~~183.150~~	~~120.000~~	~~.29335E+00~~

TABLE A3.2 AIR VISCOSITY DATA OTHER AUTHORS

TRAUTZ AND BAUMANN (1929)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.13030E-03	194.750
.15250E-03	237.550
.17990E-03	290.950
~~.19530E-03~~	~~324.450~~
.21730E-03	373.450

VASILESCO (1945)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.17200E-03	273.100
.18030E-03	289.600
.18240E-03	294.400
~~.22100E-03~~	~~379.100~~
.22940E-03	399.850

JOHNSTON AND MC CLOSKEY (1940)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.64550E-04	90.220
.64590E-04	90.280
.83500E-04	118.400
~~.92930E-04~~	~~132.780~~
.10109E-03	146.190
.11075E-03	160.890
.12386E-03	183.270
~~.13459E-03~~	~~201.590~~
.14229E-03	215.230
.15032E-03	230.520
.15845E-03	245.610
~~.16611E-03~~	~~260.350~~
.17242E-03	273.290
.17775E-03	284.600
.18514E-03	300.120

SUTHERLAND AND MAASS (1932)

VISCOSITY (POISE)	TEMPERATURE (DEG K)
.12817E-03	194.650
.18115E-03	293.950
.17083E-03	273.150
~~.15392E-03~~	~~241.550~~
.13328E-03	203.750
.11295E-03	169.150
.62690E-04	90.050
~~.55110E-04~~	~~78.950~~

KESTIN AND WANG (1958)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.18410E-03	298.150	2.000	.23690E-02
.18450E-03	298.150	5.000	.59278E-02
.18540E-03	298.150	10.000	.11873E-01
~~.18720E-03~~	~~298.150~~	~~20.000~~	~~.23805E-01~~
.18900E-03	298.150	30.000	.35781E-01
.19110E-03	298.150	40.000	.47784E-01
.19320E-03	298.150	50.000	.59797E-01
~~.19540E-03~~	~~298.150~~	~~60.000~~	~~.71800E-01~~
.19730E-03	298.150	70.000	.83776E-01
.20200E-03	298.150	80.000	.95706E-01
.20530E-03	298.150	90.000	.10757E+00
~~.20830E-03~~	~~298.150~~	~~100.000~~	~~.11935E+00~~

KESTIN AND LEIDENFROST (1960)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.19433E-03	293.150	62.160	.75859E-01
.19067E-03	293.130	48.220	.58771E-01
.18769E-03	293.130	34.970	.42527E-01
~~.18498E-03~~	~~293.150~~	~~21.400~~	~~.25939E-01~~
.18440E-03	293.150	18.030	.21834E-01
.18398E-03	293.150	14.610	.17675E-01
.18332E-03	293.150	11.220	.13560E-01
~~.18284E-03~~	~~293.150~~	~~7.790~~	~~.94041E-02~~
.18238E-03	293.150	4.390	.52935E-02
.19844E-03	298.150	69.050	.82640E-01
.19411E-03	298.130	52.170	.62408E-01
~~.19018E-03~~	~~298.140~~	~~35.120~~	~~.41926E-01~~
.18698E-03	298.140	18.010	.21427E-01

KESTIN AND WHITELAW (1964)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.18440E-03	297.710		
.19605E-03	322.290		
.20751E-03	347.120		
~~.21952E-03~~	~~374.570~~		
.24077E-03	424.310		
.22138E-03	298.250	139.470	.16466E+00
.21056E-03	297.880	109.870	.13103E+00
~~.20132E-03~~	~~297.720~~	~~82.930~~	~~.99361E-01~~
.19365E-03	297.690	55.100	.66037E-01
.18839E-03	297.670	27.950	.33381E-01
.22227E-03	322.340	124.840	.13479E+00
~~.21555E-03~~	~~322.330~~	~~100.820~~	~~.10966E+00~~
.20981E-03	322.290	77.890	.85154E-01
.20411E-03	322.320	52.100	.57134E-01
.19965E-03	322.340	25.800	.28307E-01
~~.23485E-03~~	~~347.300~~	~~142.330~~	~~.13992E+00~~
.22887E-03	347.200	116.270	.11554E+00
.22181E-03	347.160	85.510	.85832E-01
.21534E-03	347.160	55.850	.56454E-01
~~.21131E-03~~	~~347.170~~	~~28.560~~	~~.28985E-01~~
.24032E-03	376.470	127.360	.11509E+00
.23551E-03	376.380	102.520	.93594E-01
.23083E-03	375.340	78.440	.72438E-01
~~.22727E-03~~	~~375.030~~	~~52.650~~	~~.49037E-01~~
.22294E-03	374.570	25.090	.23547E-01
.25400E-03	424.360	100.690	.80871E-01
.25190E-03	424.430	80.830	.65487E-01
~~.24975E-03~~	~~424.510~~	~~59.110~~	~~.48245E-01~~
.24639E-03	424.480	40.600	.33355E-01
.24259E-03	424.320	19.780	.16363E-01
.27335E-03	469.810	104.290	.75196E-01
~~.27127E-03~~	~~470.170~~	~~82.450~~	~~.59975E-01~~
.26834E-03	470.340	62.440	.45787E-01

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.26578E-03	470.450	41.010	.30322E-01
.26240E-03	470.460	21.410	.15945E-01
.29650E-03	523.970	102.850	.66362E-01
.29425E-03	523.970	82.040	.53430E-01
.29111E-03	523.920	61.560	.46458E-01
.28764E-03	523.930	40.600	.26920E-01
.28432E-03	523.840	20.600	.13772E-01

GORING AND EAGAN (1971)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.23850E-03	423.150	36.730	.30328E-01
.24730E-03	423.150	104.790	.84272E-01

LO , CARROLL AND STIEL (1966)

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.14010E-03	203.150	20.000	.36355E-01
.15260E-03	203.150	50.000	.97070E-01
.16540E-03	203.150	75.000	.15267E+00
.17840E-03	203.150	100.000	.21045E+00
.21450E-03	203.150	150.000	.31795E+00
.27430E-03	203.150	200.000	.40066E+00
.15000E-03	223.150	20.000	.32618E-01
.16040E-03	223.150	50.000	.85017E-01
.17250E-03	223.150	75.000	.13113E+00
.18560E-03	223.150	100.000	.17812E+00
.21220E-03	223.150	150.000	.26800E+00
.25490E-03	223.150	200.000	.34418E+00

TABLE A3.2 CONT'D

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.29180E-03	223.150	250.000	.40481E+00
.16280E-03	248.150	20.000	.28982E-01
.17000E-03	248.150	50.000	.74178E-01
~~.17690E-03~~	~~248.150~~	~~75.000~~	~~.11284E+00~~
.18710E-03	248.150	100.000	.15164E+00
.21400E-03	248.150	150.000	.22643E+00
.23680E-03	248.150	200.000	.29325E+00
~~.26450E-03~~	~~248.150~~	~~250.000~~	~~.35011E+00~~
.29330E-03	248.150	300.000	.39771E+00
.17430E-03	273.150	20.000	.26124E-01
.18100E-03	273.150	50.000	.66110E-01
~~.18730E-03~~	~~273.150~~	~~75.000~~	~~.99746E-01~~
.19510E-03	273.150	100.000	.13319E+00
.21320E-03	273.150	150.000	.19772E+00
.23300E-03	273.150	200.000	.25674E+00
~~.25640E-03~~	~~273.150~~	~~250.000~~	~~.30888E+00~~
.27950E-03	273.150	300.000	.35418E+00
.30330E-03	273.150	350.000	.39339E+00
.32850E-03	273.150	400.000	.42751E+00
~~.18530E-03~~	~~298.150~~	~~20.000~~	~~.23805E-01~~
.19120E-03	298.150	50.000	.59797E-01
.19660E-03	298.150	75.000	.89748E-01
.20330E-03	298.150	100.000	.11935E+00
~~.21830E-03~~	~~298.150~~	~~150.000~~	~~.17644E+00~~
.23430E-03	298.150	200.000	.22932E+00
.25510E-03	298.150	250.000	.27707E+00
.27410E-03	298.150	300.000	.31959E+00
~~.29540E-03~~	~~298.150~~	~~350.000~~	~~.35724E+00~~
.31630E-03	298.150	400.000	.39062E+00
.33750E-03	298.150	450.000	.42035E+00
.19530E-03	323.150	20.000	.21881E-01
~~.20030E-03~~	~~323.150~~	~~50.000~~	~~.54685E-01~~
.20540E-03	323.150	75.000	.81787E-01
.21150E-03	323.150	100.000	.10847E+00

VISCOSITY (POISE)	TEMPERATURE (DEG K)	PRESSURE (ATMOS)	DENSITY (GM/CC)
.22530E-03	323.150	150.000	.15989E+00
~~.23840E-03~~	~~323.150~~	~~200.000~~	~~.20787E+00~~
.25540E-03	323.150	250.000	.25182E+00
.27420E-03	323.150	300.000	.29161E+00
.28960E-03	323.150	350.000	.32745E+00
.31170E-03	323.150	400.000	.35970E+00
~~.32540E-03~~	~~323.150~~	~~450.000~~	~~.38879E+00~~
.34290E-03	323.150	500.000	.41512E+00
.20750E-03	348.150	20.000	.20255E-01
.21250E-03	348.150	50.000	.50441E-01
~~.21600E-03~~	~~348.150~~	~~75.000~~	~~.75255E-01~~
.22180E-03	348.150	100.000	.99620E-01
.23270E-03	348.150	150.000	.14655E+00
.24600E-03	348.150	200.000	.19055E+00
~~.26110E-03~~	~~348.150~~	~~250.000~~	~~.23124E+00~~
.27530E-03	348.150	300.000	.26853E+00
.29230E-03	348.150	350.000	.30255E+00
.30610E-03	348.150	400.000	.33352E+00
~~.32240E-03~~	~~348.150~~	~~450.000~~	~~.36175E+00~~
.33810E-03	348.150	500.000	.38754E+00
.35340E-03	348.150	550.000	.41117E+00
.21830E-03	373.150	20.000	.18861E-01
~~.22270E-03~~	~~373.150~~	~~50.000~~	~~.46849E-01~~
.22660E-03	373.150	75.000	.69777E-01
.23120E-03	373.150	100.000	.92245E-01
.24100E-03	373.150	150.000	.13551E+00
~~.25040E-03~~	~~373.150~~	~~200.000~~	~~.17621E+00~~
.26350E-03	373.150	250.000	.21411E+00
.27610E-03	373.150	300.000	.24916E+00
.28970E-03	373.150	350.000	.28143E+00
.30420E-03	373.150	400.000	.31110E+00
~~.31830E-03~~	~~373.150~~	~~450.000~~	~~.33838E+00~~
.32450E-03	373.150	500.000	.36350E+00
.34630E-03	373.150	550.000	.38667E+00

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