VISCOSITIES OF NATURAL GASES AT HIGH PRESSURES AND HIGH TEMPERATURES

A Thesis

by

ANUP VISWANATHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2007

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	William D. McCain Jr.
Committee Members,	Larry D. Piper
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ABSTRACT

Viscosities of Natural Gases at High Pressures and High Temperatures.

(May 2007)

Anup Viswanathan, B.Tech., Anna University, India

Chair of Advisory Committee: Dr. William D. McCain, Jr.

Estimation of viscosities of naturally occurring petroleum gases provides the information needed to accurately work out reservoir-engineering problems. Existing models for viscosity prediction are limited by data, especially at high pressures and high temperatures. Studies show that the predicted viscosities of natural gases using the current correlation equations are about 15 % higher than the corresponding measured viscosities at high pressures and high temperatures.

This project proposes to develop a viscosity prediction model for natural gases at high pressures and high temperatures.

The project shows that commercial gas viscosity measurement devices currently available suffer from a variety of problems and do not give reliable or repeatable results. However, at the extremely high pressures encountered in high pressure and high temperature reservoirs, the natural gases consist mainly of methane as the hydrocarbon constituent and some non-hydrocarbon impurities. Available viscosity values of methane were used in the development of a correlation for predicting the viscosities of naturally occurring petroleum gases at high pressures and high temperatures. In the absence of measurements, this correlation can be used with some confidence.

DEDICATION

This thesis is dedicated to the Almighty God, for the love, wisdom, and protection he has granted me up until this moment in my life. It is dedicated to my loving, caring, and supportive family, for all their prayers and support needed to complete this work.

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude and appreciation to the following people who greatly contributed, in no small measure, to this work:

- Dr. William D. McCain, Jr., Visiting Professor of Petroleum Engineering, who served as the chair of my graduate committee. His knowledge, experience, and support guided me to the completion of this work. It has being a real pleasure and privilege to work under such supervision.
- Drs. Larry Piper, Kenneth Hall, and Catalin Teodoriu, for serving as members of my graduate committee.
- Additionally, Mr. Frank Platt for helping me in each step of setting up the High Pressure High Temperature laboratory for this project.

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CHAPTER I

INTRODUCTION

1.1 Viscosity of Fluids

The Merriam-Webster dictionary defines Viscosity as “the property of resistance to the flow of a fluid”. Viscosity describes a fluid’s internal resistance to flow and may be thought of as a measure of fluid friction. Viscosity of liquids is usually easier to perceive than the viscosity of gases, being in most cases an order of magnitude higher. Viscosity of liquids ranges across several orders of magnitude.

Explained in terms of molecular origins, the viscosity in gases arises principally from the molecular diffusion that transports momentum between layers of flow. Typically, the viscosity of gases is a function of both its pressure and temperature except in the dilute gas state. For temperatures higher than the critical temperature, and moderate pressures, the dilute gas state is approached. In this dilute gas state the pressure dependence fades away. However, for the gases considered by the scope of the study, the viscosity was always found to be a function of the pressure.

Newton’s theory of viscosity states that the shear stress (τ) between adjoining layers of a fluid is proportional to the velocity gradient ($\partial u/\partial y$), in a direction perpendicular to the layers. Mathematically this can be represented as

$$\tau = \mu \frac{\partial u}{\partial y} \tag{1.1}$$

This thesis follows the form and style of the *SPE Reservoir Evaluation and Engineering.*

where μ, the constant of proportionality is the dynamic viscosity (Pa.s). This is pictorially represented in fig. 1.1.

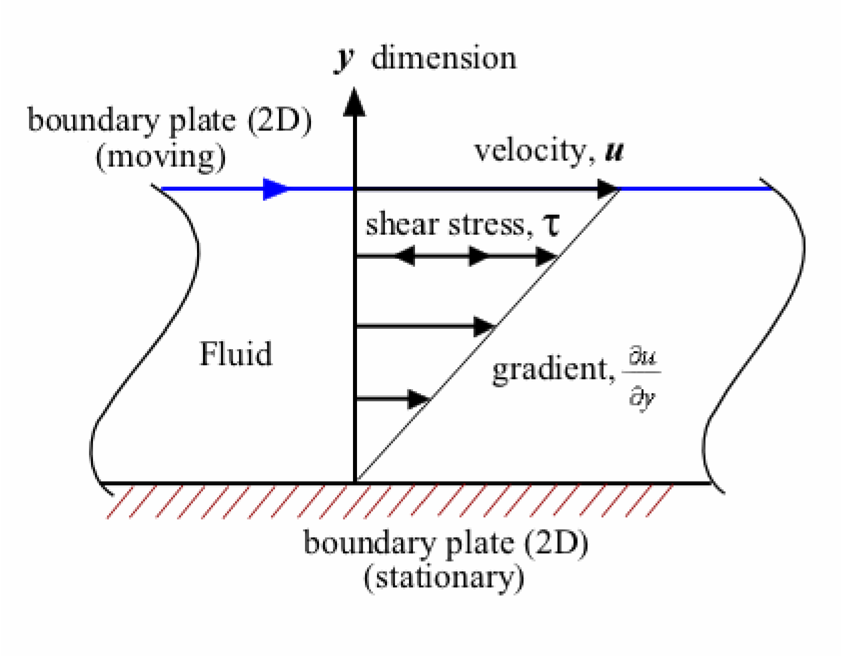

Figure 1.1—Laminar shear in fluids, after wikipedia.com

The S.I. unit of dynamic viscosity is Pascal-second, identical to $kg.m^{-1}.s^{-1}$. The cgs physical unit of dynamic viscosity is Poise, named after Jean Louis Marie Poiseuille. The other commonly used measure of viscosity is kinematic viscosity, the ratio of viscous force to the inertial force, the latter characterized by the fluid density ρ. The S.I. unit of kinematic viscosity is $m^2.s^{-1}$ and the cgs unit is stokes, named after George Gabriel Stokes. Dynamic viscosity is usually measured, kinematic viscosity is calculated.

1.2 Importance of Viscosity in the Petroleum Industry

The two most important aspects of viscosity in the petroleum industry are flow and storage. These define the quantity of hydrocarbons that are present in the reservoir, and the quantity that can be effectively recovered. The viscosity of hydrocarbon fluids thus acquires significance and importance.

Gas viscosity is harder to measure compared to oils and quite often service companies do not carry out these measurements in the laboratory. Instead, the laboratory uses viscosity correlations to predict the viscosity of the gas given the temperature, pressure, and specific gravity of the sample. For reservoirs having moderate pressures, temperatures, and relatively lean gases these correlations yield satisfactory results.

In the quest for more oil and gas, drilling technology has considerably advanced allowing very deep drilling operations to be viable, both technically and economically. The depth of these wells causes pressures and temperatures to be extremely high. These wells are also referred to as High Pressure High Temperature (HPHT) wells. At these extreme pressures, and temperatures the reservoir fluids will be very lean gases, mostly methane. The industry however continues to use the viscosity correlations that were developed for moderate pressures and temperatures to these HPHT problems. This leads to erroneous estimates of the gas viscosities and hence mistakes in reservoir engineering calculations.

1.3 Laboratory Measurement of Gas Viscosity

The measurement of the viscosity of any fluid, liquid or gas can be carried out in many ways. The most common and the most popular equipments used in the measurement of viscosity of gases are:

- Rolling ball viscometer

- Falling body viscometer
- Capillary tube viscometer
- Vibrating wire viscometer

Using any of these viscometers in the measurement of gas viscosity involves making an adjustment to the system. This is due to the low density of gases. The dry nature of most gases also hinders the measurement process due to erratic friction in the measurement process.

Rich natural gases usually contain some percentage of heavier components, making the viscosity measurement of these gases relatively easier than other gases. However, for lean (or dry) natural gases, which essentially is just methane, measuring viscosity can be difficult.

Measurements of viscosities of nitrogen and methane have been carried out at various temperatures and pressures including high pressures and high temperatures using a rolling ball viscometer and a modified falling body viscometer.

1.4 Analysis of Gas Viscosity Data

There are numerous sources of data of gas viscosities available for low and intermediate pressures in the range of 4000 – 10000 psia. However, there are very few published sources of accurate data at high pressures and high temperatures. One of the deliverables of the project is to correlate high pressure high temperature gas viscosity data to help in its prediction. Statistical analysis including non-linear regression offers a solution to this problem, by helping to extend the current correlations into the high pressure high temperature regime.

1.5 Objectives

The objectives of this research are as follows:

- Review the literature to understand the state of the art in gas viscosity measurement procedures. Review the literature to gather the measured data on natural gas viscosities and also the viscosities of its biggest constituent, methane, especially at high pressures and high temperatures. Review the existing gas viscosity prediction correlations and highlight the correlation used commonly in the petroleum industry.
- Measure the viscosities of gases at high pressures and high temperatures in the laboratory.
- Correlate the available high temperature and high pressure methane viscosity data using non-linear regression procedures to extend the currently used correlation.

CHAPTER II

LITERATURE REVIEW

2.1 Review of Viscometer Equipments

Commercial and laboratory viscometers have come a long way from those developed during the time of Reynolds, who was one of the first people attributed to commercial viscometers, because of his theory on critical velocity. Through gradual development over the years, the most successful and important viscometers of all times use one of the following six principles:-

1. Rolling sphere
2. Falling body
3. Capillary tube
4. Vibrating wire

It is important to note that not all of these above techniques can be used for measurement of viscosity of gases without making hydrodynamic corrections and approximations for ends, edges and walls. These corrections when known, are often large, and are the primary source of error. Given below is a brief description of some of the techniques that has been successfully applied to the measurement of viscosity of gases.

2.1.1 Rolling Ball Viscometer

The use of the system of the inclined tube and rolling ball as a viscometer was first suggested close to a 100 years back by Flowers[1]. Flowers used the principle of dimensional analysis to correlate the variables involved in the system. This combined the various parameters involved into groups of dimensionless variables making the analysis easier. Later, Hubbard and Brown[2] also used dimensional analysis to derive relations between the variables involved and the calibration of the rolling ball viscometer. Most studies involving the application of rolling ball viscometers are for liquids, and very few are actually for gases. Liquid viscosity measurement is easier since liquids have higher absolute viscosities as compared to gases. High viscosity fluids have a greater roll time which makes the measurements easier. Pressure maintenance is also easier for systems built primarily for liquids. Hence most of the viscometers existing in the literature are for liquids measurement. In fact, in the last twenty years no rolling ball viscometers have been reported as being used for measurement of gas viscosities. However, for the sake of completeness of this study, rolling ball viscometers are discussed in further detail owing to their historical value.

Measuring principle: The rolling ball viscometer utilizes the principle of travel time of the ball through a known distance to measure the viscosity of the fluid. The system setup is as follows - a tube of a known length is set at a known inclination in an isothermal system - a metal or glass ball of a known diameter is rolled down the tube containing the fluid. As long as the flow around the rolling ball is laminar, the viscosity is directly proportional to the travel time.

$$\mu \propto t \tag{2.1}$$

However this relation can be extended to the turbulent region too, but involves empirical correlations. This was investigated by Sage and Lacey[3], who measured the viscosity of methane and two hydrocarbon gases with a few procedural modifications as described in their work.

Defining equation: The rolling ball viscometer measures the absolute viscosity of any fluid using the following general equation

$$\mu = K \cdot t \cdot (\rho_b - \rho) \tag{2.2}$$

The constant K incorporates the geometry of the system, including the diameters of the ball and the pipe, and the angle of inclination of the pipe with the horizontal among other parameters.

Since the parameter K is a function of the angle of inclination, there exist different values of K for each angle investigated. Fig. 2.1 shows a typical rolling ball viscometer with all the important parts labeled.

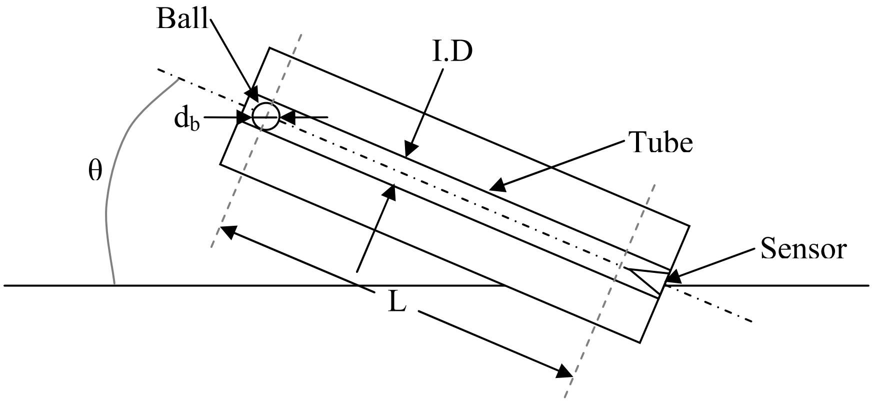

Figure 2.1—Typical rolling ball viscometer

Operating procedure: All rolling ball viscometers, before they can be used, need to be calibrated using known liquids. The calibration procedure mainly gives an estimate of the constant K, as a function of the temperature to be used in the viscosity equation. A rolling ball viscometer also requires a very accurate method for calculating the roll time. This involves detecting the ball as it crosses certain pre-determined points of the tube. For example, the contact type rolling ball viscometer measures the elapsed time between the breaking of the upper contact point and the making of the lower contact. This variant of the rolling ball viscometer was used by Sage and Lacey[3] and by Bicher and Katz[4]. The contact type rolling ball viscometer looks very similar to the typical rolling ball viscometer shown in fig. 2.1, with the tip of the sensor acting as the contact for the rolling ball. Another alternative to this is to use capacitance meters. The rolling time of the ball is measured on a strip chart between the signals produced by an FM capacitance meter, as it passes through sets of ring-shaped electrodes spaced along the viscometer cell. This was used by Harrison and Gosser[5] and is shown in fig. 2.2.

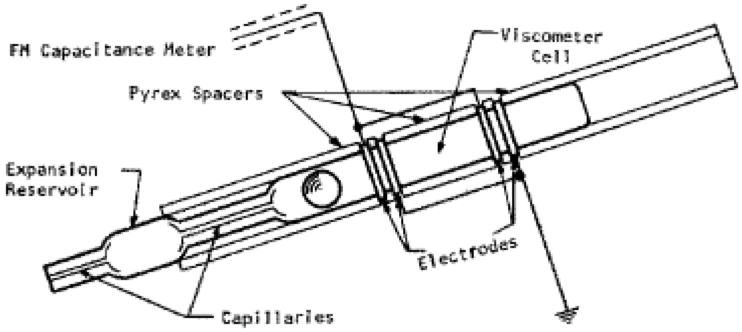

Figure 2.2—Viscometer cell, after Harrison and Gosser[5]

Another version of the rolling ball viscometer uses optical detector as was investigated by Sawamura[6] *et al*. The schematic of this instrument is shown in fig. 2.3.

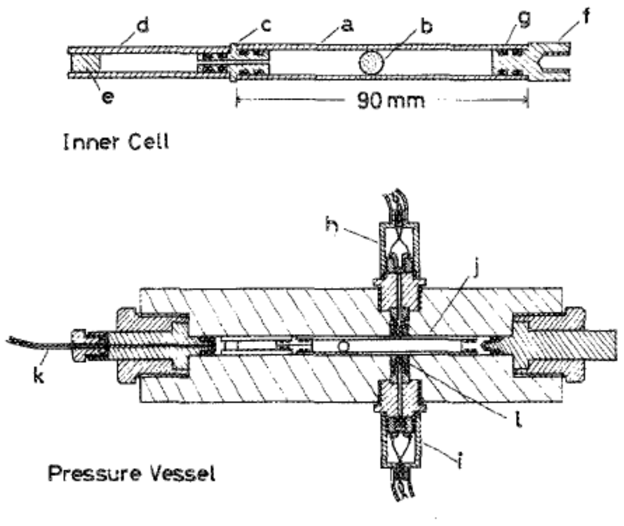

Figure 2.3—Inner cell and pressure vessel, after Sawamura *et al*[6]

The parts of the viscometer are: a. Glass tube, b. Glass ball, c. Connection, d. Glass cylinder, e. Glass piston, f. Connector to the pressure vessel, g. O-ring, h. Detector, i. Lamp, j. Inner cell, k. High pressure tube, and l. Sapphire windows

Izuchi and Nishibata[7] used differential transformers to detect the rolling ball in their equipment, developed for pressures greater than 100,000 psi. Their viscometer cell is shown in fig. 2.4.

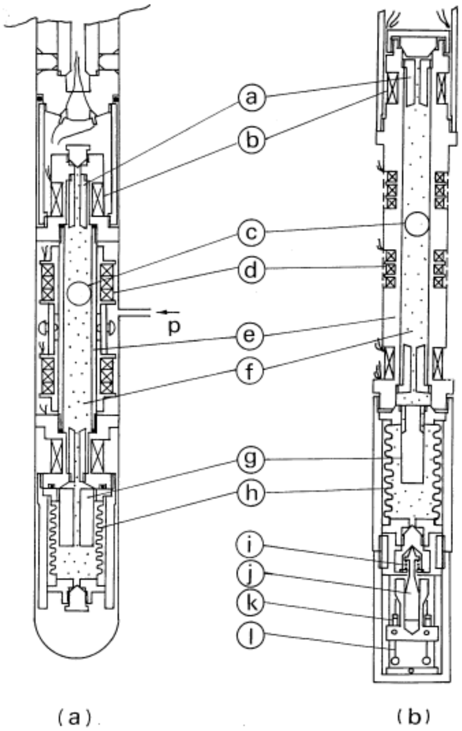

Figure 2.4—Rolling ball viscometer, after Izuchi and Nishibata[7]

(a) Original viscometer cell design

(b) Improved design assembled with the potentiometer

The parts of this viscometer are: a. Permalloy cylinder, b. Retaining coil, c. Ball, d. Differential transformer, e. Tube, f. Sample liquid, g. Spacer, h. Bellows, i. Coil spring, j. Connecting stem, k. Leaf spring contact, and l. Manganin wire

Limitations: Sage and Lacey[3] reported lesser accuracy at higher pressures using their equipment than at lower pressures. However, it is important to note that the highest pressure investigated was 2900 psi. They further point out that there is no single-valued functional relationship between the roll time and the absolute viscosity under conditions of turbulent flow. The accuracy of the rolling ball viscometer depends on the accuracy of measurement of the roll time. Since the rolling ball viscometer is a kinematic viscometer it requires a secondary device for measuring the density of the fluid.

Published results: Most published results for gas viscosity measurements using rolling ball viscometers do not extend to very high pressures. Sage and Lacey[3] carried out their investigation to a pressure of 2900 psi. Even though other works have been undertaken to study the viscosity of gases using this equipment, this equipment has not been used very extensively for natural gases. Bicher and Katz[4] used the rolling ball viscometer to measure the viscosities of the Methane-propane system up to a pressure of 5000 psi for various temperatures. They observed an average deviation of about 3% from Sage and Lacey[3].

Sage and Lacey[3] presented viscosity of methane and one sample of lean natural gas at three different temperatures and pressures up to 2900 psi. Viscosity of methane as a function of pressure is shown in fig. 2.5.

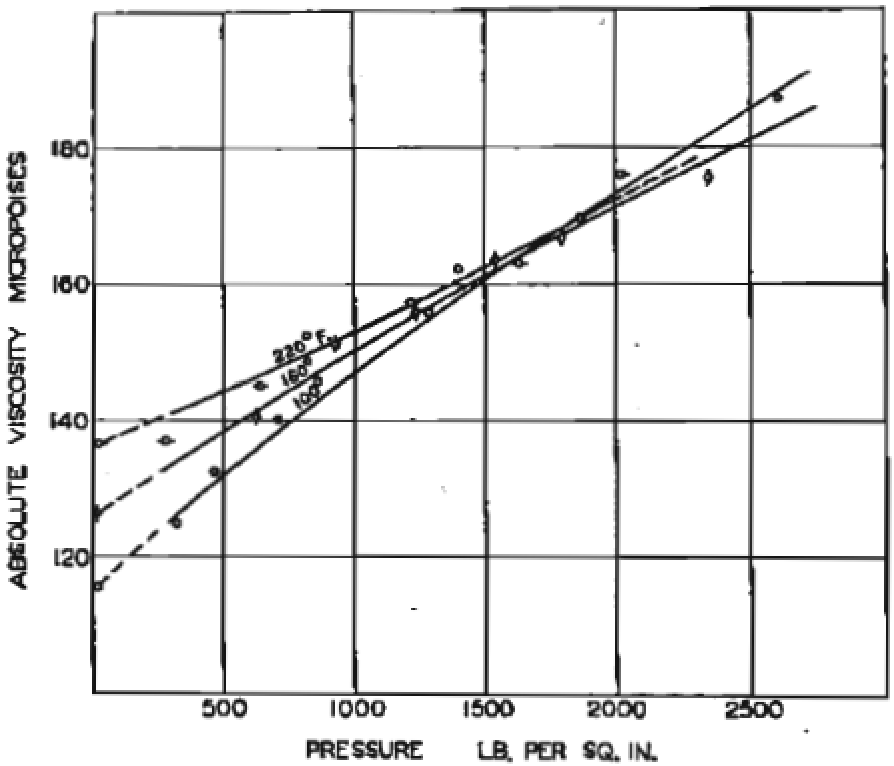

Figure 2.5—Measured viscosity of methane, after Sage and Lacey[3]

2.1.2 Falling Body Viscometer

The falling body viscometer is very similar to the rolling body viscometer with the exception that the ball is replaced with a piston. In most cases the viscometer is vertical. Thus the piston is always free falling under gravity. The falling body viscometer is better suited for viscosity measurements since no slipping can occur as in the case of the rolling ball. It is also more applicable to the turbulent flow region. Like rolling ball viscometers falling body viscometers have been used to measure the viscosity of liquids. Gases, having very low viscosities are not very well suited for vertical arrangements since the falling body takes very short time to traverse the known distance.

Measuring principle: The measuring principle of the falling body viscometer is similar to the rolling ball viscometer. The time taken for the body to fall through a known distance gives a direct estimation of the viscosity of the fluid. The main theoretical consideration for the falling body viscometer was given by Stokes[8]. Stokes[8] carried out his analysis for a sphere falling through an infinite, viscous medium, Barr[9] proposed modifications to Stokes's original work using a shape factor for other geometries.

Operating procedure: The density of the falling body is greater than that of the fluid. Thus, some external means are required for suspending the falling body in the viscous medium. The viscometer cylinder usually has an electromagnet at the top which holds the falling body until it is ready to be released. Older falling body viscometers did not have such a provision. The viscometer was physically inverted to bring the falling body to the top and re-inverted when the experiment was begun. The magnetic type of falling body viscometer was discussed by Swift *et al*[10] and further used by Swift *et al*[11] and Lohrenz *et al*[12] to carry out experiments on liquid viscosities. However, these studies were carried out nearly fifty years back. More recently Chan and Jackson[13] used this same principle in a falling body viscometer which used a laser Doppler to analyze the travel time of the falling body. Their viscometer is shown in fig. 2.6.

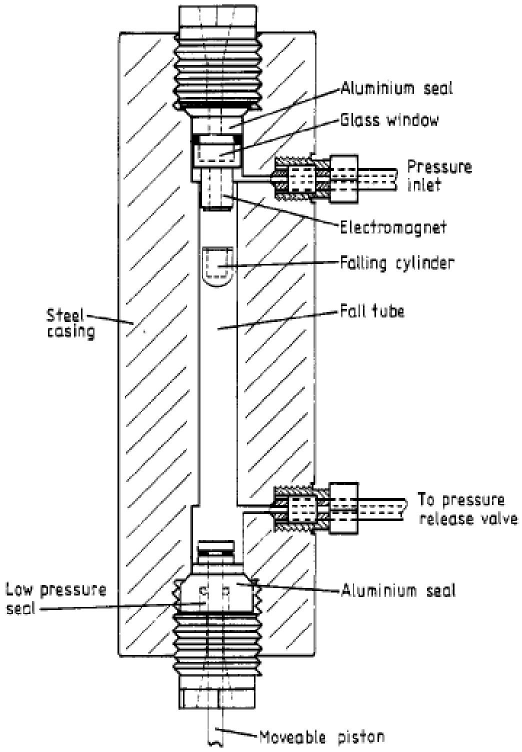

Figure 2.6—Falling body viscometer, after Chan and Jackson[13]

Chan and Jackson used a Michelson interferometer to measure the Doppler shift of the laser beam after it is reflected off the back of the falling cylinder. Their viscometer however was built for operations with liquids and the viscosity range was also much higher than those encountered with gases. The cross section of the falling cylinder is shown in fig. 2.7.

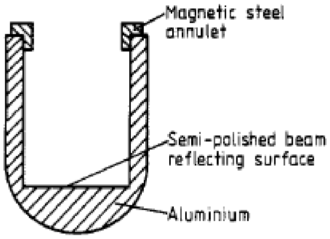

Figure 2.7—Falling cylinder, after Chan and Jackson[13]

Daugé *et al*[14] used a viscometer which was essentially similar to the one used by Chan and Jackson. The detection system was based on electromagnetic effect induced by the sinker passing through sets of coils located at different depths of the measuring cell. Their system is shown in fig. 2.8.

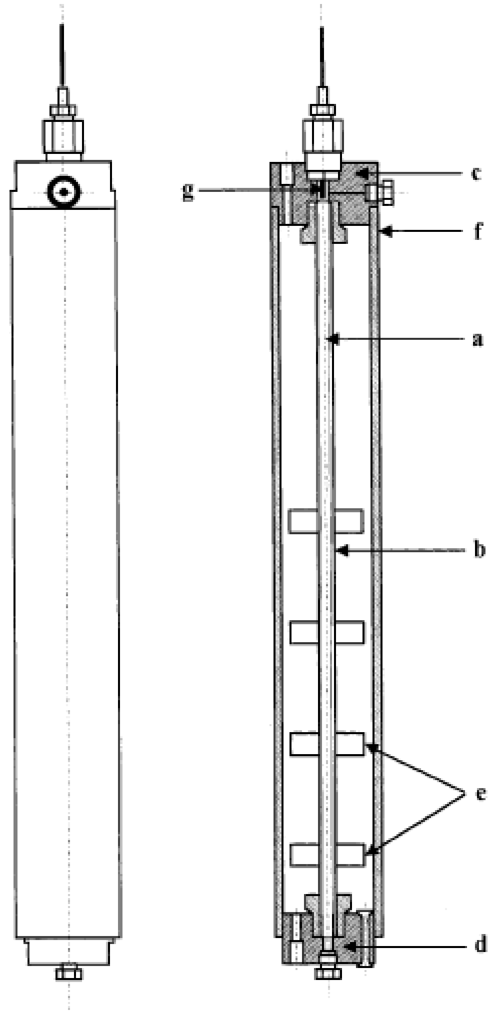

Figure 2.8—Measuring cell used by Daugé *et al*[14]

The parts of the measuring cell are: a. Inner tube, b. Cylindrical outer tube, c. Top high pressure connector, d. Bottom high pressure connector, e. Electrical coils, f. Heating jacket, and g. Temperature probe

The falling body used by Daugé *et al* is also just slightly different from the one used by Chan and Jackson. This is shown in fig. 2.9. The falling body is made of Aluminum and contains a magnetic core as shown by (a) and (b) in fig. 2.9.

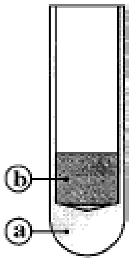

Figure 2.9—Falling body, after Daugé *et al*[14]

The authors used the viscometer to study the viscosities of mixtures of methane and n-decane in the liquid state at various temperatures and pressures.

Bair[15] developed a viscometer capable of measuring viscosities up to 145000 psi. This was used mainly for organic liquids applied to the field of elasto-hydrodynamic lubrication. The schematic is shown in fig. 2.10.

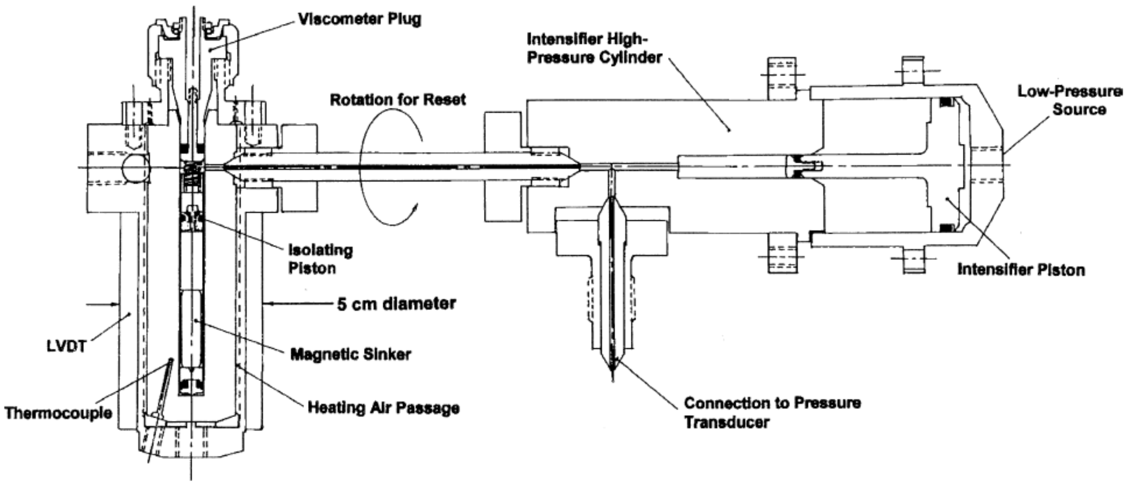

Figure 2.10—Viscometer assembly, after Bair[15]

Papaioannou, Bridakis, and Panayiotou[16] used a falling body viscometer to study the thermophysical properties of hydrogen-bonded liquids, mainly alcohols. Their viscometer was self-centering in nature and used magnetic inductance as the detection principle. The viscometer is shown in fig. 2.11.

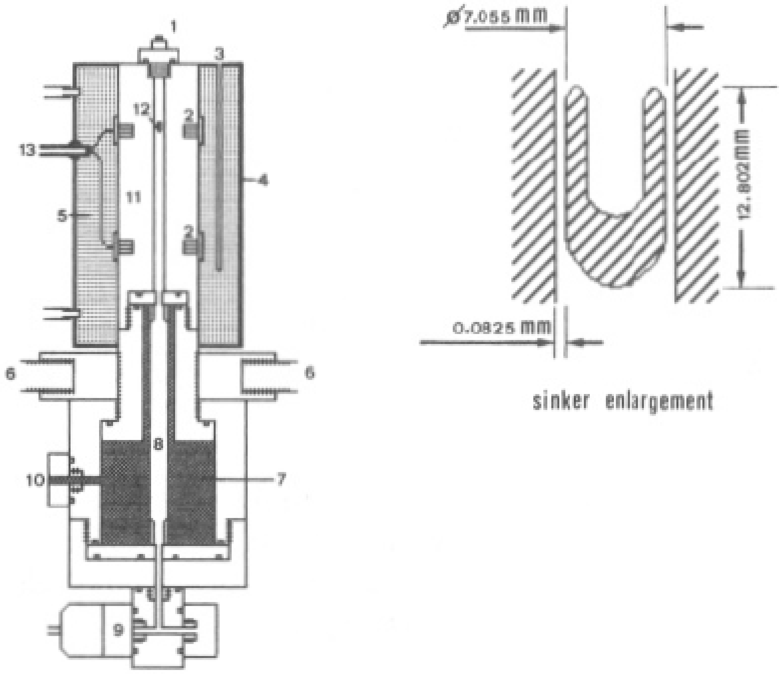

Figure 2.11—Cross section of viscometer and sinker, after Papaioannou *et al*[16]

The parts of their viscometer are: a. Crub screw plug, b. Triggering coils, c. Temperature sensor, d. Thermostatic jacket, e. Circulating thermostatic fluid, f. bearing bars, g. Hydraulic compression fluid, h. Flexible Teflon tube filled with studied fluid, i. Pressure transducer, j. Connection to dead-weight tester, k. viscometer tube, l. sinker, and m. exit of electric cables

Limitations: The falling body viscometer suffers from a very serious disadvantage that since the body falls vertically it is not well suited for measuring gas viscosities. Falling body viscometers have proved quite satisfactory in the measurement of liquid viscosities.

Published Results: Due to the limitations above, the falling body viscometer has not been used very extensively for measuring gas viscosities. In fact, most of the references found in the literature indicate the same. Swift *et al*[11] used the falling body viscometer to measure the viscosities of the four lightest alkanes in their liquid state. The pressures were quite low at around 700 psi, and the temperatures were maintained such that the samples remained in the liquid state. Chan and Jackson[13] exhibited the ability of their viscometer to operate at high pressures by measuring the viscosity of octane at around 15000 psi. Daugé *et al*[14] used their viscometer to measure the viscosity of a mixture of methane and decane for temperature up to 210 °F and pressure up to 20300 psi.

2.1.3 Modified Falling Body Viscometer

The main disadvantage of the falling body viscometer is that since the cylinder falls vertically down the tube, the time of travel is very short. This can however be overcome by making the whole arrangement horizontal or nearly horizontal. Keeping it horizontal gives the added advantage of nullifying any gravity effects. But because there is no gravity assistance in driving the cylinder piston, some external means have to be applied. Even though the literature does not contain many references to investigations using the modified falling body viscometer, the equipment used to carry out the bulk of the experiments in this study is a type of modified falling body viscometer. The details of this equipment are discussed below.

Cambridge Viscosity Inc. VISCOpvt system: The VISCOpvt is the viscometer designed by Cambridge Viscosity, Inc. exclusively for measuring viscosities of petroleum fluids, oils and gases. The measurable range of the gas viscosity is from 0.02 to 0.2 cP. The viscometer has an operating pressure range to 25000 psi and temperatures to 350 °F. The VISCOpvt has been traditionally used for measurement of oil viscosities and has only in the last few years been exposed to the measurement of gas viscosities. The accuracy of the VISCOpvt is reported to be around 1% of full scale of range.

Measuring principle: The Cambridge VISCOpvt works on the principle of a known piston traversing back and forth in a measuring chamber containing the fluid sample. The piston is driven magnetically by two coils located at opposite ends. The time taken by the piston to complete one motion is correlated to the viscosity of the fluid in the measuring chamber by a proprietary equation. A schematic of the Cambridge VISCOpvt system is shown in fig. 2.12. This schematic includes the modifications that were performed in the laboratory to make the system more efficient and to resolve any pressure leak problems that might creep into the system, especially at very high pressures.

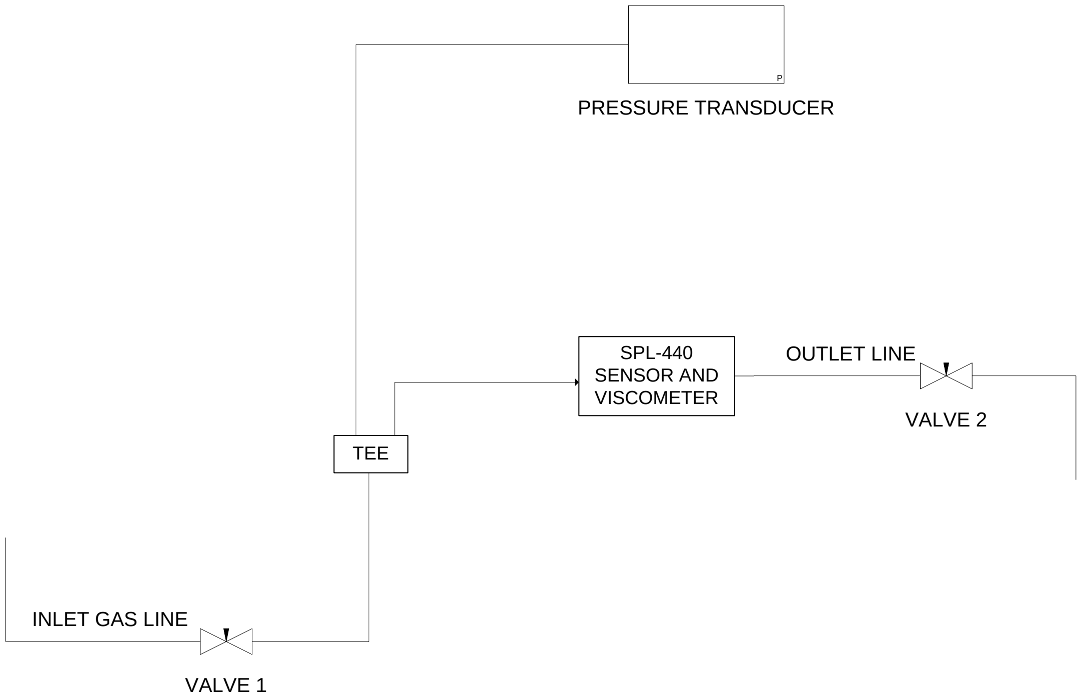

Figure 2.12—Schematic of the Cambridge VISCOpvt system (modified)

A brief description of the various components of the system is given below. Valve 1 is the inlet valve to the system (It is CLOSED after sample has been injected). Valve 2 is the outlet valve from sensor (It is CLOSED while the system is in operation). SPL-440 Sensor and Viscometer is angled at 45° for liquid mode operation, horizontal for gases. The pressure transducer is rated for continuous pressure measurements to 30000 psi. The viscometer schematic is shown in fig. 2.13.

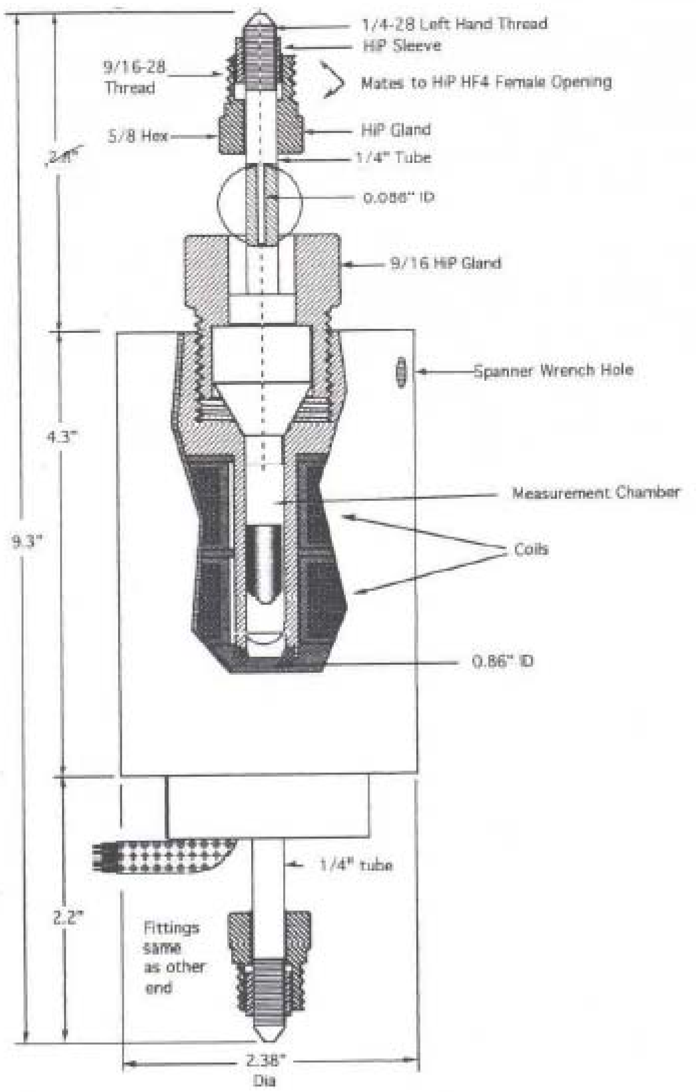

Figure 2.13—SPL 440 sensor viscometer schematic, after Thomas *et al*[17]

The piston has to be first calibrated against a fluid of known viscosity. The first step of the calibration takes place at the high end of the measurement range. This procedure determines the drive speed of the magnetic coils. After this has been satisfactorily and accurately achieved, the measurement chamber is filled with a low-end fluid for the second stage of the calibration procedure. A low-end fluid is defined as a fluid that has its reference viscosity close to the low end of the measurement range. This time however, no change is made to the drive level of the piston. A low-end correction factor is made to for any small adjustment that might be required to bring the measured viscosity to the correct level. The high-end fluid is refilled into the measurement chamber and the high end correction factor is checked and applied as needed.

Published results: Thomas *et al*[17] used the VISCOpvt viscometer system to measure the viscosity of a water-wet natural gas. They observed that at pressures higher than 6000 psi, the metal in the measuring chamber undergoes expansion and this effect has to be accounted for using a pressure correction equation. Fig. 2.14 shows the measured viscosity without pressure correction.

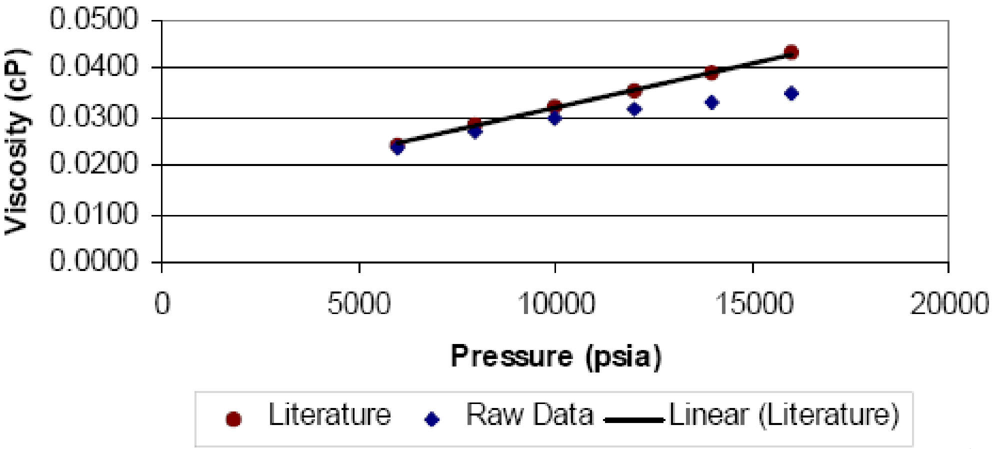

Figure 2.14—Measured viscosity of water-wet gas, after Thomas *et al*[17]

The measured viscosity thus has to be scaled up by using a factor which is a function of the pressure. The pressure correction equation used by Cambridge Viscosity is given below.

$$\mu_c = \mu_m \times \left(\frac{A + 4.61\times10^{-5} \times P}{A} \right)^{2.875} \tag{2.3}$$

The difference between measured and calculated viscosities was shown again by Thomas *et al* in fig. 2.15.

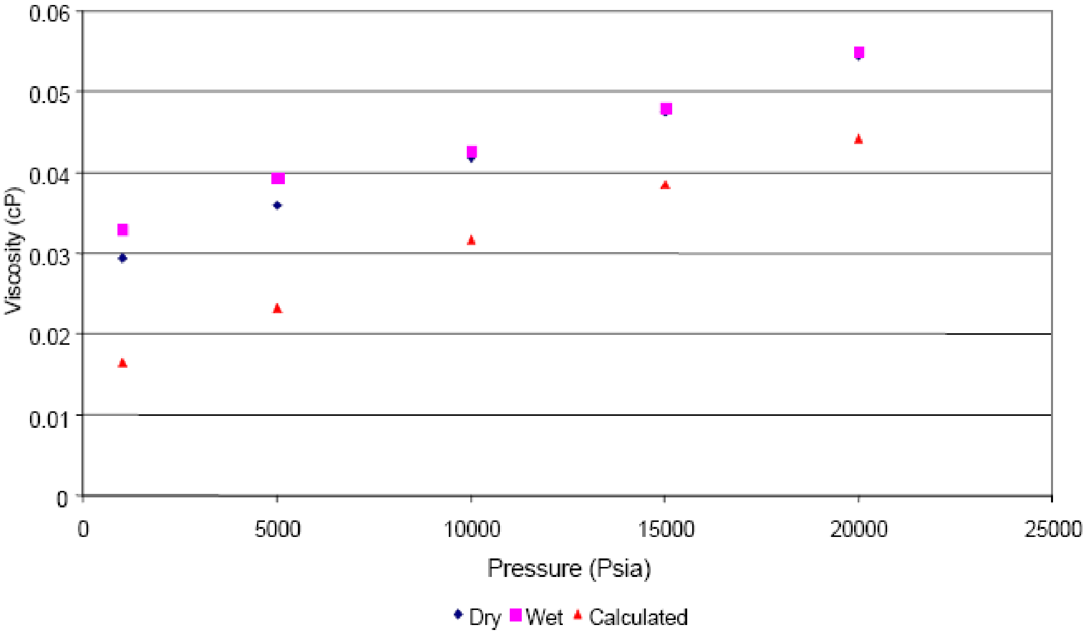

Figure 2.15—Measured and calculated viscosity, after Thomas *et al*[17]

Thus, Cambridge Viscosity, along with Thomas *et al* developed a pressure correction correlation to account for the expansion of the measurement chamber at higher pressures and temperatures.

2.1.4 Capillary Tube or Rankine Viscometer

The basic principle of operation of the Rankine method is that a pellet of clean mercury, introduced into a properly sized glass tube filled with a gas, completely fills the cross section of the tube. Forming a perfect internal seal between the spaces on its either side, the mercury pellet will, at any inclination of the tube, quickly come to a steady descending velocity. This descending pellet acts as a piston, forcing the gas through a fine capillary. The steadiness of the descent can be appreciably improved by using a precision-bore Pyrex tube.

This mercury "piston" establishes a constant pressure difference across the fine capillary. Although the work done by the descending pellet is used principally against viscous forces in the gas, some is dissipated in other ways. Some of these forces can be considered negligible as was shown by Rankine[18, 19].

The weight of the pellet and the internal diameters of both tubes being known, the time of descent of the mercury between given points permits calculation of the volume rate of flow of the gas through the capillary under constant pressure difference, providing data which allows the computation of the viscosity of the gas.

Different methods have been used to measure the timing of the fall of the pellet. Comings, Mayland, and Egly[20] used electrical contacts in the wall of the fall tube. The falling mercury pellet makes alternatively makes and breaks an electrical circuit which controls the timing device. However, even though this method is simple, it sometimes leads to problems, especially when using narrow-bore capillary tubes. Additionally, the contact subdivides the mercury pellet especially at higher pressures. Carr[21] solved the problem of timing the fall of the mercury pellet by using a sensitive electronic instrument. Rings, fastened to the fall tube at desired positions, are connected to a sensitive, capacity detecting instrument. When mercury enters the top ring, the instrument detects the capacity change and automatically starts the timer. The timer is stopped when the pellet enters the bottom ring.

Carr used two capillary tube viscometers to measure the viscosities of methane and three pipeline gas mixtures. These measurements were made to pressures as high as 10000 psi over a temperature range of 70 °F to 250 °F.

2.1.5 Vibrating Wire Viscometer

The falling body and the capillary tube methods of measuring the viscosities of fluids involve making hydrodynamic corrections and approximations for ends, edges, and walls. These corrections when known, are often large, and are a major source of error. The vibrating wire viscometer is based on the damping of the transverse vibrations of a taut wire in the fluid, and minimizes or eliminates hydrodynamic correction terms. The viscosity is obtained from a decay time measurement, and requires knowledge of the fluid density. The technique can be well applied to all fluids of low viscosities. Tough, McCormick, and Dash[22] were the first to use the vibrating wire technique in the measurement of low viscosity fluids. They measured the viscosity of liquid helium in the range of 0.02 cP at very low temperatures.

Theory of vibrating wire in a viscous fluid: Consider a wire of length l, mass per unit length ζ, and radius a, fixed at both ends and subjected to a tension T. Let the wire be immersed in a fluid of density ρ and viscosity μ. The stretched wire is situated in a transverse magnetic field, and is deflected when a direct current is passed through it.

When the wire has attained a steady deflection, the current is switched off and the wire is connected to the input of a low noise amplifier. The alternating voltage induced by the decaying vibrations of the wire across the magnetic field are amplified, displayed on an oscilloscope and photographed. A second exposure is made at a higher sweep rate to measure the frequency. The decay constant τ is then obtained from the photograph by plotting the output signal amplitude on semi-log paper, fitting a straight line to the points and calculating the slope. The solution for the damping of an infinite cylinder in a viscous medium can be applied to the vibrating wire. The result is that a wire which undergoes transverse vibrations at a frequency ω damps with a decay time given by

$$\Lambda = \frac{2(\zeta + \zeta')}{\pi a^2 \rho k'(m)} . \tag{2.4}$$

Here m is one-half the ratio of the wire radius to the viscous penetration depth λ.

$$m = \frac{a}{2\lambda} \tag{2.5}$$

$$\lambda = (\mu/\omega\rho)^{1/2} \tag{2.6}$$

The solution given by equation 2.5 is valid under the condition that m is greater than one-half. The meaning of this condition is that the penetration depth not be larger than the radius of the wire. The total hydrodynamic mass of the wire in the fluid is given by ζ',

$$\zeta' = \pi \rho a^2 k(m) \tag{2.7}$$

and the functions k(m) and k'(m) are given in fig. 2.16. For large values of m, the approximation

$$k'(m) = \frac{\sqrt{2}}{m} + \frac{1}{2\sqrt{m}} \tag{2.8}$$

can be used. Assuming that the nuisance damping and the added hydrodynamic mass of the wire can be neglected, the viscosity is given by

$$\mu = \frac{a^2 \omega \rho}{4[k'(m)]^2} \tag{2.9}$$

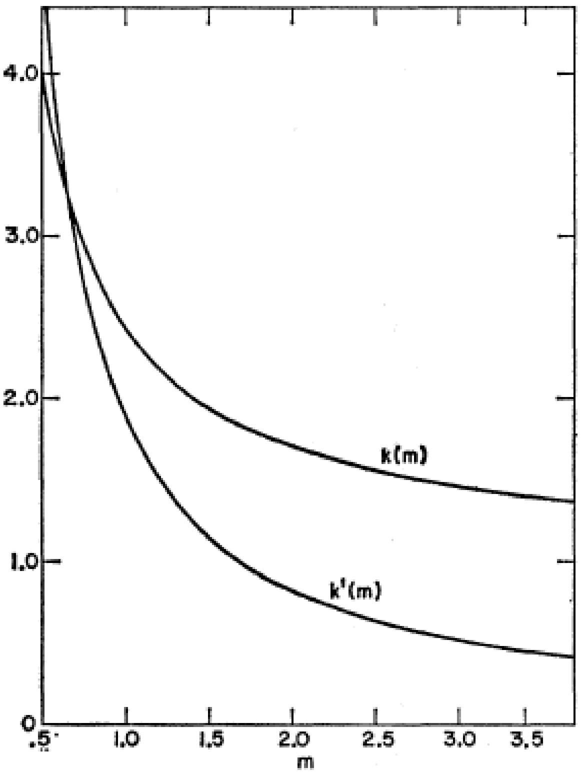

Figure 2.16—Functions k(m) and k'(m) used in vibrating wire viscometers

A typical vibrating wire viscometer is shown in fig 2.17.

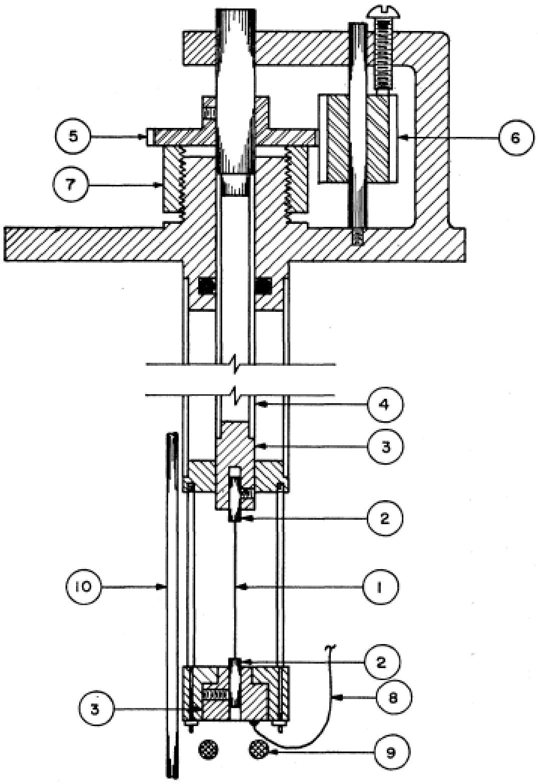

Figure 2.17—Details of the vibrating wire viscometer, after Tough *et al*[22]

The various parts of the apparatus are 1. Tungsten wire, 2. Stainless steel tubing soldered to wire, 3. Brass chucks, 4. Control rod, 5. Primary Control gear, 6. Secondary Control gear, 7. Tension control, 8. Electrical lead soldered to lower chuck, 9. Carbon resistors for thermometry, and 10. Manometer tube.

To ensure that wall corrections need not be made in the calculations, the structural members of the apparatus should be kept as far as convenient from the wire. Although no exact correction for the effect of a wall, Tough, McCormick, and Dash[22] indicate that it is quite negligible if the wall is about 100 wire radii from the wire. Trappeniers, van der Gulik, and, van den Hooff[23] developed a vibrating wire viscometer to measure the viscosity of gases at high pressures. Fig 2.18 shows their viscometer.

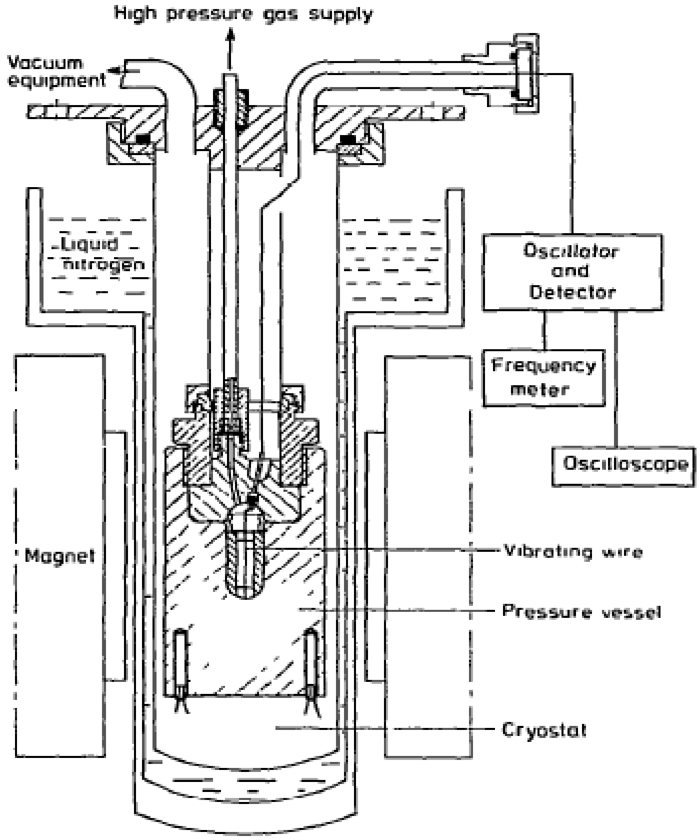

Figure 2.18 – Vibrating wire viscometer, after Trappeniers *et al*[23]

Published results: Tough, McCormick, and Dash[22] used the vibrating wire viscometer to measure the viscosity of liquid helium at very low temperatures. The measured viscosity at those temperatures was in the range of expected viscosities of gases. Wilhelm *et al*[24] designed a vibrating wire viscometer capable of measuring the viscosities of both dilute and dense gases for pressures as high as 5800 psi and temperatures up to 480 °F. Bruschi and Santini[25] used the vibrating wire viscometer and measured the viscosity of argon gas at a temperature of 70 °F and pressures from atmospheric pressure to 440 psi. At these conditions, the measured viscosities were in the range of 0.2 – 0.22 cP. Trappeniers, van der Gulik, and van den Hooff[23] measured the viscosity of argon at various temperatures and pressures; the highest temperature was 122 °F. The authors investigated various pressures in the range from 14500 psi to 113000 psi. The measured viscosities were in the range from 0.07 cP to 0.77 cP. van der Gulik, Mostert, and van den Berg[26] used a vibrating wire viscometer to measure the viscosity of methane at 77 °F and pressures up to 145000 psi.

2.2 Review of Viscosity Data

The viscosities of gases play an important role in many engineering calculations especially those involving fluid flow. Viscosity affects the pressure drop due to friction in the pipeline transmission of natural gas. The friction factor is a function of the roughness factor and Reynolds number, which depends on the viscosity. The flow rate of the gas is determined by its viscosity, and this affects the flow of gas from the reservoir, or into the reservoir, when it is injected. In each of these calculations, the viscosity must be evaluated at operating conditions, specifically the pressure and temperature, and compositions in case of gas mixtures.

Current drilling practices have enabled the petroleum industry to drill deeper in its quest for more oil and gas. The bottom-hole conditions of these very deep wells often reach temperatures of around 350 °F and pressures in the vicinity of 20000 psia. The knowledge of the viscosity of natural gas is of special importance in the prediction of its movement underground, as well as the open flow potential.

Rich natural gas usually contains more than 95 % methane by volume. Even in case of sour gases or heavier natural gases, seldom does the concentration of methane drop below

80% by volume. However, these are the concentrations of gases in case of shallow to moderate wells. Due to the extreme high temperature of the deeper wells drilled now, almost all of the natural gas is methane, with some impurities such as nitrogen, carbon dioxide and hydrogen sulfide. Thus, a large part of this study is devoted towards the viscosity of methane at high pressures and high temperatures.

A thorough search of the literature revealed that most of the published data on the viscosity of methane or naturally occurring petroleum gases were extremely limited in both range and quantity, and their accuracy is doubtful. It was previously mentioned that the viscosity of natural gases must be evaluated at operating conditions. Since it is not always possible to measure the viscosity at a given temperature and pressure, the petroleum industry often resorts to published correlations. However, it is important to note that any correlation is only as good as the data it is based upon. Moreover, the more data any correlation is based upon, the more accurate it will be in predicting the property.

The viscosity correlations currently employed by the petroleum industry are based on limited data, most of which are at low pressures and temperatures. These correlations may yield incorrect viscosity when applied to high pressure and high temperature problems. The problem, therefore, is to add to the databank of both methane and natural gas viscosity, especially at high pressures and high temperatures. These viscosities can be applied to extend the current correlations to high pressures and high temperatures.

Carr[21], as part of work done at the Institute of Gas Technology, carried out measurements of viscosities of natural gas components and mixtures. He used a capillary tube viscometer in his work. The principle of the capillary tube viscometer is briefly explained in the previous chapter. Carr's objective was to develop the necessary equipment and procedures for determining the viscosities of methane and several natural gas mixtures at pressures up to 10000 psia.

Carr carried out experiments to measure the viscosity of methane and three other natural gases. The natural gases however were synthetically prepared in the laboratory and were not naturally occurring gases. Viscosity data for methane was determined at average temperatures of 71 °F, 75 °F, 77 °F, 152 °F, and 200 °F up to pressures of 8000 psia. The 75 °F isotherm is shown in fig. 2.19.

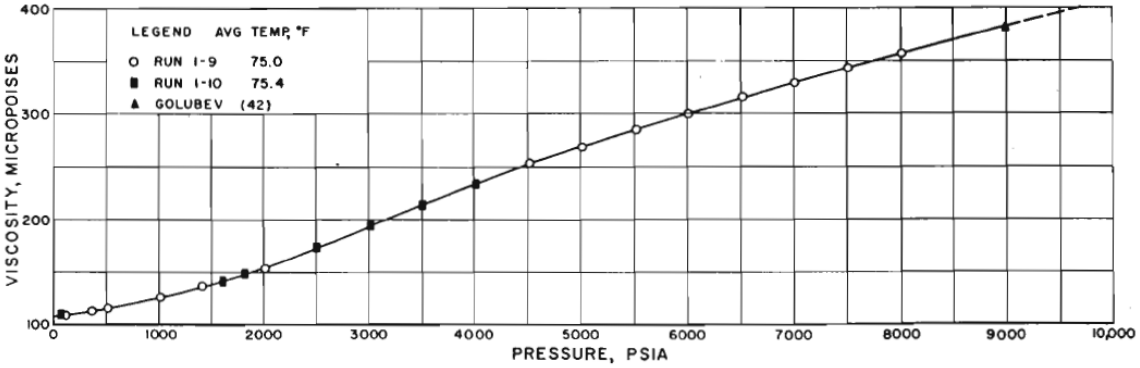

Figure 2.19—Viscosity of methane at 75 °F, after Carr[21]

Carr carried out two separate runs at about the same average temperature. Viscosities measured by both runs are consistent and the trend agreed with Golubev[27]. Out of the three synthetic natural gases tested one was a high-ethane gas containing about 25% ethane, high nitrogen gas containing about 16% nitrogen and low ethane gas containing about 96% methane. Measurements on all the three gases were carried out at about the same temperatures as methane up to pressures of about 9000 psia. Viscosity of the low-ethane natural gas is shown in fig. 2.20.

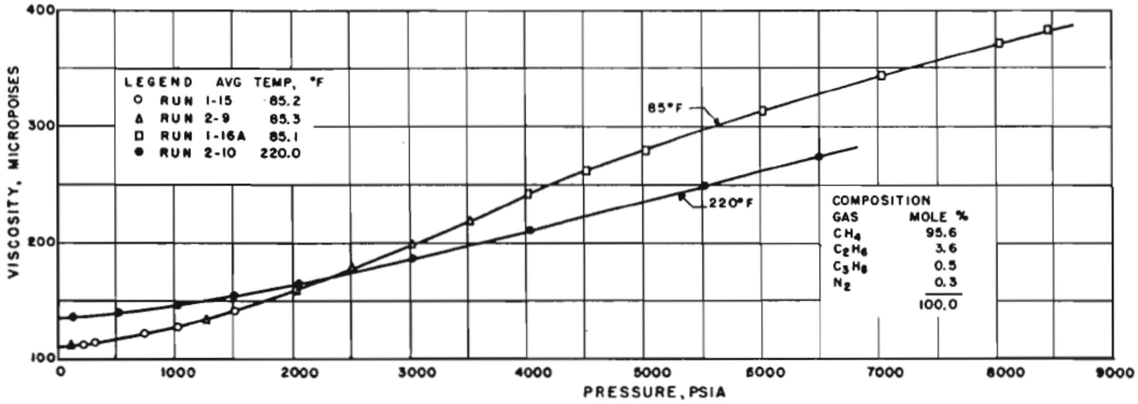

Figure 2.20—Viscosity of low-ethane natural gas, after Carr[21]

The figure above shows the viscosity of the gas at two different temperature isotherms, 85 °F, and 220 °F. Carr's work was significant in that it was the first effort of this magnitude to understand and document the viscosity of natural gas and its components at high pressure.

2.3 Carr, Kobayashi, and Burrows Correlation

To address this problem Carr, Kobayashi, and Burrows[28] used the above data sets along with other data previously obtained by Comings, Mayland, and Egly[20] and correlated them as functions of reduced pressures and temperatures. Fig. 2.21 shows the viscosity ratio as a crossplot function between pseudo-reduced pressure and pseudo-reduced temperature. Viscosity ratio is defined as the ratio of the viscosity of a gas, at a given temperature and pressure, to the viscosity of the gas at the same temperature but at atmospheric pressure.

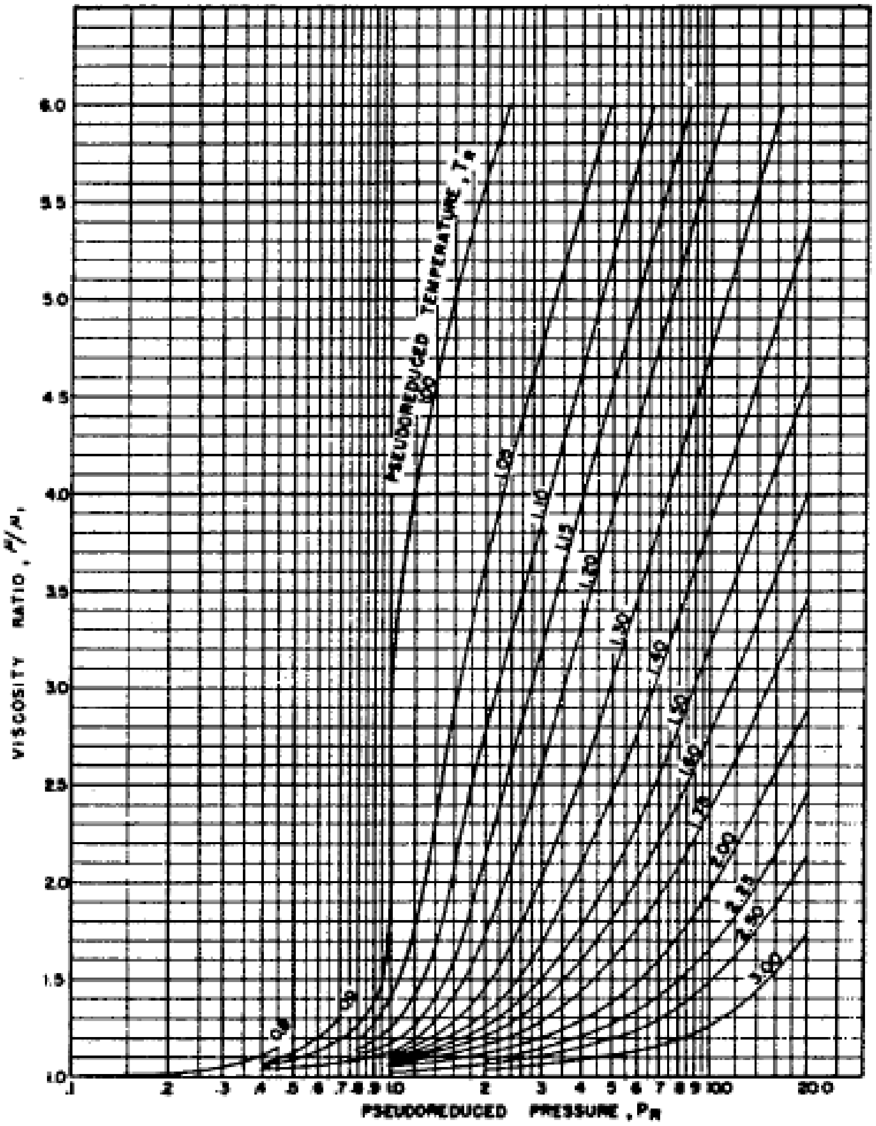

Figure 2.21—Viscosity ratio versus pseudo-reduced pressure, after Carr *et al*[28]

The average deviation of the predicted viscosity ratio from experimental points used in the correlation was found to be approximately 1.5 %. The maximum deviation of 5.4 % occurred at reduced pressures greater than 10. Carr, Kobayashi, and Burrows presented a stepwise procedure to use their crossplots to determine viscosities of natural gases from gas gravity.

The usefulness of the Carr, Kobayashi, and Burrows procedure in predicting the viscosities of complex hydrocarbon mixtures is dependent on the prediction of the atmospheric viscosities of mixtures by relatively simple means. Figure 2.22 shows the viscosity ratio as a function of pseudo-reduced temperature for various values of pseudo-reduced pressure.

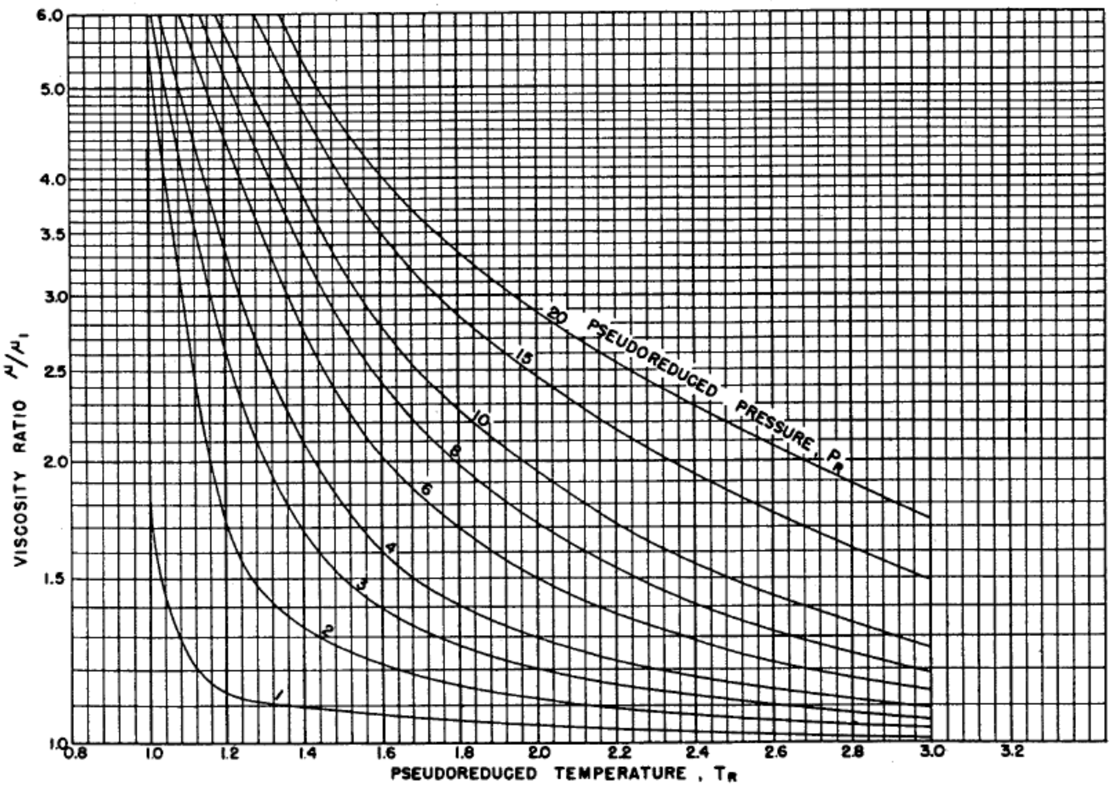

Figure 2.22—Viscosity ratio versus pseudo-reduced temperature, after Carr *et al*[28]

Bicher and Katz[4] used the viscosities of natural mixtures containing a moderate amount of isomers to develop a plot of viscosity versus molecular weight. This plot was proposed by Bicher and Katz to determine the viscosity of hydrocarbon gas mixtures at atmospheric pressure. Bicher and Katz observed that the viscosities of most mixtures read from their plot agreed with experimental values obtained by other authors. The agreement in all cases over the concentration range is within 1 %. Either the molecular weight, or gas gravity, defined below can be applied to their figure to determine the atmospheric viscosities.

$$Gas\ gravity, G = \frac{Density\ of\ Gas\ at\ 60°F, 14.7\ psia}{Density\ of\ dry\ Air\ at\ 60°F, 14.7\ psia} \tag{2.10}$$

Non-hydrocarbon components occur quite frequently in natural mixtures of hydrocarbons. The most common of these non-hydrocarbon components are nitrogen, carbon dioxide, and hydrogen sulfide. The kinetic behavior of non-hydrocarbon components differs considerably from hydrocarbons of the same molecular weight. Hence the molecular weight-viscosity relationship of these components cannot be expected to correlate with the hydrocarbons. Bicher and Katz used correction factors for the presence of non-hydrocarbon components in natural gases. Bicher and Katz assumed a linear effect of concentration to apply over the concentration range from 0 to 15 mole per cent of non-hydrocarbons. Further, the presence of each of the non-hydrocarbons is to increase the viscosity of the hydrocarbon mixtures. Fig. 2.23 shows the viscosity of gases at atmospheric pressure against both molecular weight and gas gravity. The insert plots are the corrections to be applied to account for the presence of non-hydrocarbons.

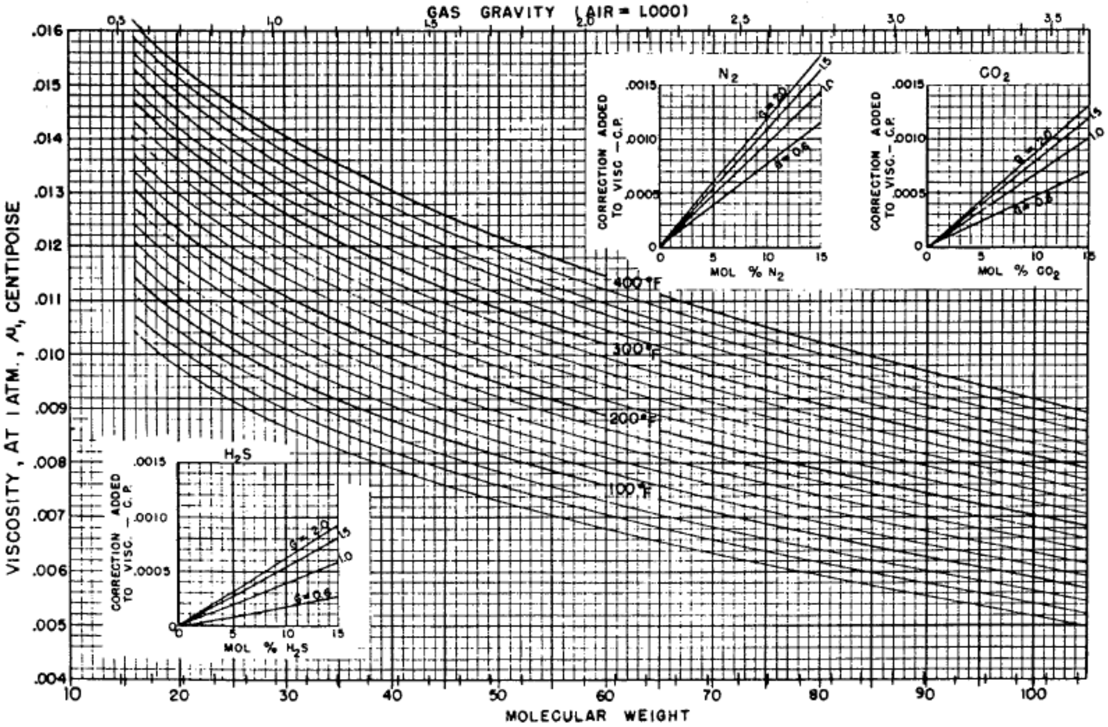

Figure 2.23—Viscosity of hydrocarbon gases at one atmosphere, after Carr *et al*[28]

Carr, Kobayashi, and Burrows state that in order to obtain the effect of pressure on viscosity, it is necessary to know the pseudo-reduced pressure and temperature of the mixture. If the gas analysis is known, the pseudocriticals used to compute the pseudo-reduced pressure and temperature may be computed using equations below.

$$T_{pc} = \sum_{i=1}^{n} x_i T_{ci} \tag{2.11}$$

$$p_{pc} = \sum_{i=1}^{n} x_i p_{ci} \tag{2.12}$$

However, the pseudo-critical temperatures and pressures of natural gases can be correlated with gas gravity. The correlation obtained by Bicher and Katz in fig. 2.24 may be used to obtain the pseudo-critical pressure and temperature of natural gases. These can then be used to determine the pseudo-reduced pressure and temperature. Insert plots are again provided to indicate the direction and magnitude of errors introduced in the pseudo-critical predictions by the presence of non-hydrocarbon constituents. However, the authors state very clearly that these corrections are hypothetical in nature.

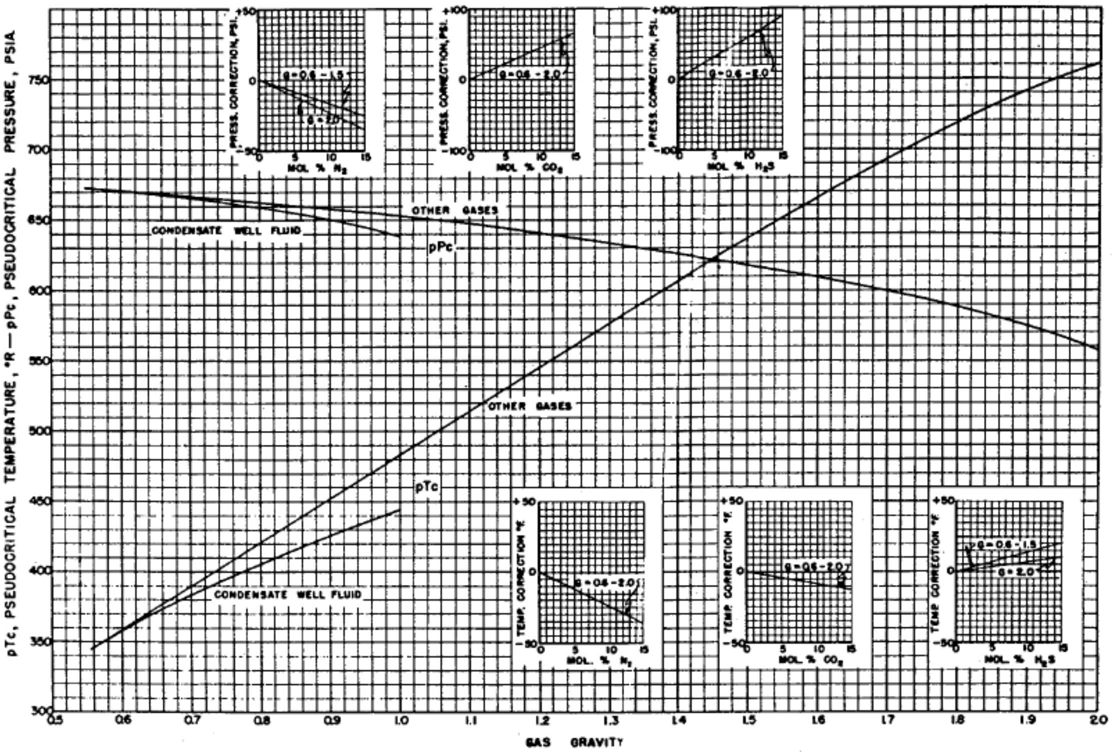

Figure 2.24—Prediction of pseudo-critical properties from gas gravity, after Carr *et al*[28]

The procedure for determining viscosities of natural gases from gas gravity is explained by Carr, Kobayashi, and Burrows as follows.

1. Determine the pseudo-critical pressure and temperature of the natural gas, either by using the equations or fig. 2.24. Corrections should be made to these pseudo-critical properties for the presence of non-hydrocarbon gases. In case the compositions of the gas phase are available, the calculated pseudo-critical properties are recommended.

2. Divide the known pressure by the pseudo-critical pressure to obtain the pseudo-reduced pressure. In similar manner, divide the known temperature by the pseudo-critical temperature to obtain the pseudo-reduced temperature. All pressure’s are in psia and all temperatures are in °R.
3. From the pseudo-reduced pressure and temperature, obtain the corresponding viscosity ratio from figures 2.21 and 2.22.
4. Obtain the viscosity of the gas at atmospheric pressure from fig. 2.23.
5. Convert the viscosity ratio to the absolute gas viscosity, by multiplying the viscosity ratio by the viscosity of the gas at one atmosphere.

2.4 Lohrenz, Bray, and Clark Correlation

Even though Carr, Kobayashi, and Burrows determined the viscosity of gaseous hydrocarbon mixtures as functions of pressure, temperature, and phase composition, their analysis procedure is based upon the knowledge of gas specific gravity. Lohrenz, Bray, and Clark[29], on the other hand carry out an analysis to correlate the viscosity of natural gases as a function of pressure, temperature, and composition. Lohrenz, Bray, and Clark used the same data points as used by Carr, Kobayashi, and Burrows.

In compositional material balance computations, the compositions of the reservoir gases are known. The calculation of the viscosities of these fluids using this information is required for a true and complete compositional material balance. In compositional material balance calculations, the oil-gas viscosity ratio is always used as a multiplier with the relative permeability ratio. Since the relative permeability ratio is subject to large uncertainties, the accuracy requirement of the viscosity predictions is not severe. The authors state that average deviations of ±25 % should be acceptable. However, Lohrenz, Bray, and Clark agree that better accuracy is desirable, since the viscosity prediction procedures have other uses apart from compositional material balances.

To carry out the Lohrenz, Bray, and Clark procedure to determine the viscosity of the gas, the composition must be given in mole fractions of hydrogen sulfide, carbon dioxide, nitrogen, and the hydrocarbons methane to heptanes-plus fraction. Their calculation procedure splits the butane and pentane fractions into their normal and iso components. As in most cases, the hexane fraction includes all hexane isomers. Another important requirement for the procedure to be applied is the knowledge of the average molecular weight and specific gravity of the heptanes-plus fraction. Based on the compositional knowledge of the gas, the viscosity can be calculated as a function of temperature and pressure of the gas.

Calculating the viscosity of the gas using the Lohrenz, Bray, and Clark procedure involves the following steps.

1. Break-up the heptanes-plus fraction into a mixture of normal paraffin hydrocarbons from C_7 through C_{40}. The mole fraction of each hydrocarbon is determined C_i is determined as follows

   $$x_{C_i} = x_{C_6} \exp\left(A(i-6)^2 + B(i-6)\right) \tag{2.13}$$

   where i ranges from 7 to 40. The constants A and B are determined such that

   $$x_{C_{7+}} = \sum_{i=7}^{40} x_{C_i} \tag{2.14}$$

$$x_{C_{7+}} M_{C_{7+}} = \sum_{i=7}^{40} \left(x_{C_i} M_{C_i} \right) \tag{2.15}$$

2. Calculate the low-pressure pure component gas viscosities at the temperature of interest for all components in the mixture. Lohrenz, Bray, and Clark suggest using the Stiel and Thodos[30] correlation as shown below

$$T_{rj} = \frac{T}{T_{cj}} \tag{2.16}$$

$$\zeta_j = \frac{T_{cj}^{1/6}}{M_j^{1/2} p_{cj}^{2/3}} \tag{2.17}$$

Depending on the value obtained for the reduced temperature of the particular component, one of the following two equations should be used.

$$\mu_j^* \zeta_j = 34(10^{-5}) T_{rj}^{0.94} \quad \left(T_{rj} < 1.5 \right) \tag{2.18}$$

$$\mu_j^* \zeta_j = 17.78(10^{-5}) \times \left(4.58 T_{rj} - 1.67 \right)^{0.94} \quad \left(T_{rj} > 1.5 \right) \tag{2.19}$$

All the above equations require the temperature to be in °K and pressure in atm. The result of the calculation is a table of values of μ_j^* for all pure components.

3. Calculation of the low-pressure mixture gas viscosity at the temperature of interest using the Herning and Zipperer[31] equation

$$\mu^* = \frac{\sum_{j=1}^{n} \left(x_j \mu_j^* \sqrt{M_j} \right)}{\sum_{j=1}^{n} \left(x_j \sqrt{M_j} \right)} \tag{2.20}$$

4. Calculate the reduced temperature and pressure of the mixture using molal average pseudo-critical values

$$T_r = \frac{T}{\sum_{j=1}^{n} x_j T_{cj}} \tag{2.21}$$

$$p_r = \frac{p}{\sum_{j=1}^{n} x_j p_{cj}} \tag{2.22}$$

5. Calculate the viscosity of the gas mixture at the temperature and pressure of interest using the chart of Baron, Roof, and Wells[32] giving

$$\frac{\mu}{\mu^*} = F(T_r, p_r) \tag{2.23}$$

The viscosity ratio is read from that chart and the desired viscosity is calculated.

Application of the Lohrenz, Bray, and Clark procedure to various available data points yields an average absolute deviation of about 4 %. Application of the procedure to the data set of Carr[21] yields an average absolute deviation of 2.1 %.

2.5 Lee, Gonzalez, and Eakin Correlation

The above two projects and correlations were a start for the petroleum industry with the need to accurately model the viscosity of reservoir fluids; especially natural gases. One of the most comprehensive studies on the viscosity of naturally occurring petroleum gases was carried out by Lee, Gonzalez, and Eakin[33] in 1964. The authors along with other co-workers at the Institute of Gas Technology performed measurements on various pure light hydrocarbons. Lee *et al*[34] were the first to develop a correlation equation to predict the viscosity of light hydrocarbon gases. Their correlation equation is based upon measured viscosity data on ethane, propane, and normal-butane. Even though their correlation had excellent accuracy when applied to pure components, little progress could be made to fit it to mixtures. This was mostly because of paucity of detailed data on mixtures in the literature.

To address this issue of lack of adequate and suitable data for gas mixtures, Gonzalez, Eakin, and Lee[35] carried out a project to study the viscosity of natural gases. The scope of the project was to measure the viscosities of eight different natural gases, with varying proportions of methane and other components. The compositions of the different gases used are provided in table 2.1. Surprisingly enough, none of the gases sampled contained any hydrogen sulfide. The equipment used to carry out these measurements was a capillary tube viscometer, much like that described in the previous chapter.

Table 2.1—Compositions of natural gases (%), after Gonzalez *et al*[35]

Gas	**Sample Number**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
N_2	0.21	5.2	0.55	0.04	0.00	0.67	4.8	1.4
CO_2	0.23	0.19	1.7	2.04	3.2	0.64	0.9	1.4
He	0.00	0.00	0.00	0.00	0.00	0.05	0.03	0.03
C_1	97.8	92.9	91.5	88.22	86.3	80.9	80.7	71.7
C_2	0.95	0.94	3.1	5.08	6.8	9.9	8.7	14
C_3	0.42	0.48	1.4	2.48	2.4	4.6	2.9	8.3
n-C_4	0.23	0.18	0.50	0.58	0.48	1.35	1.7	1.9
i-C_4	0.00	0.01	0.67	0.87	0.43	0.76	0.00	0.77
C_5	0.09	0.06	0.28	0.41	0.22	0.6	0.13	0.39
C_6	0.06	0.06	0.26	0.15	0.1	0.39	0.06	0.09
C_{7+}	0.03	0.94	0.08	0.13	0.04	0.11	0.03	0.01
Total	**100.02**	**100.02**	**100.04**	**100.00**	**99.97**	**99.97**	**99.95**	**99.99**

The authors used the Lee *et al* correlation to predict the viscosity of the natural gases used by them in their study at the pressure and temperature of interest. The particular set of parameters contained in the equations reproduced experimental data to within ±5%. The authors realized that even though this correlation was reasonably accurate, better density values would give better viscosity results. The authors thus sought the easiest and most accurate density prediction method and applied it along with a generalized compressibility factor chart to modify the previous correlation. The result of their effort was a set of correlations similar to that of Lee *et al* but with a different set of parameters. The improved correlation reproduced the experimental data with a standard deviation of ±2.69% and a maximum deviation of 8.99 %.

The procedure for using the Lee, Gonzalez, and Eakin correlation is very simple and involves the use of the following equations

$$\mu = K \exp(X\rho^{Y}) \tag{2.24}$$

$$K = \frac{0.0001 \times (7.77 + 0.0063M)T^{1.5}}{122.4 + 12.9M + T} \tag{2.25}$$

$$X = 2.57 + \frac{1914.5}{T} + 0.0095M \tag{2.26}$$

$$Y = 1.11 + 0.04X \tag{2.27}$$

The knowledge of the temperature, the density, and the molecular weight of the natural gas sample is sufficient to determine the viscosity using the Lee, Gonzalez, and Eakin correlation.

The temperatures and pressures investigated by Gonzalez, Eakin, and Lee ranged from 100 °F to 340 °F, and atmospheric to 8000 psia respectively. Even though the temperatures were evenly distributed, the bulk of the data were for pressures below 5000 psia, with only 10 per cent of the data in the pressure range 5000 to 8000 psia.

As an example, fig. 2.25 shows a part of the viscosity data for natural gas sample 2 as described above in the composition table. Since the gas was about 98 % methane, we would expect that the gas would have most of the characteristics of pure methane. The correlation appears to be the most accurate at lower temperatures and not so much at the highest temperature. In fact, even the measured data at the highest temperature are inconsistent.

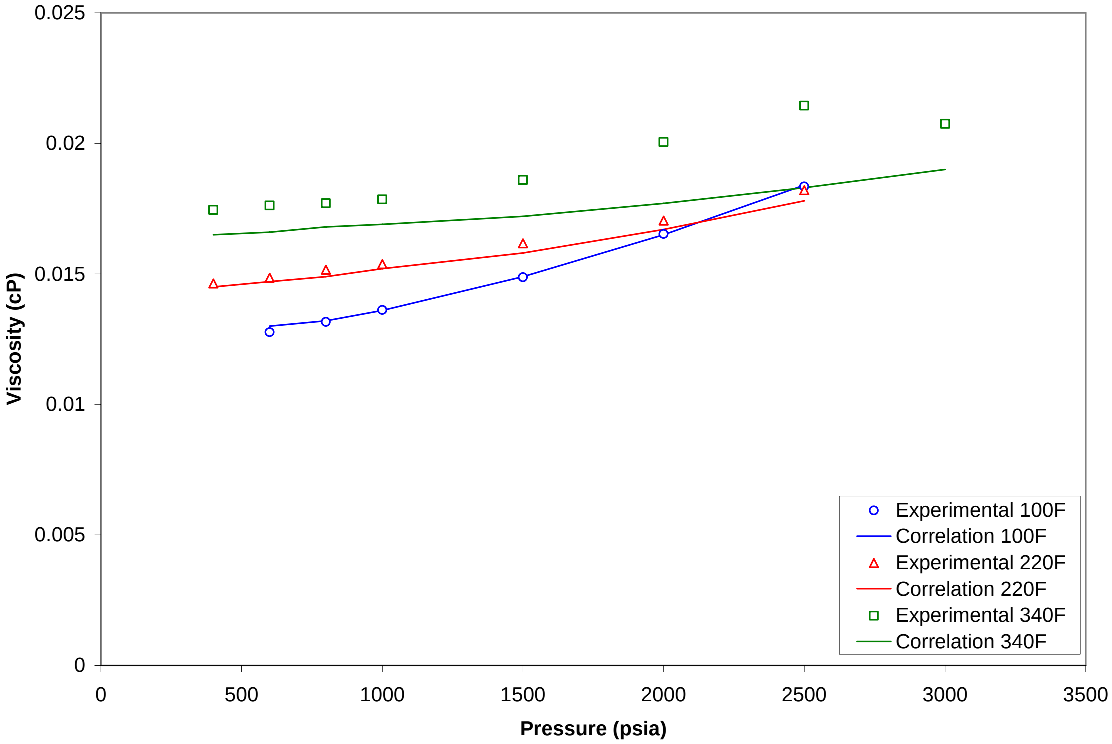

Figure 2.25—Viscosity of natural gas sample 2, after Gonzalez *et al*[35]

From the discussion above, it is clearly evident that there still is a need in the petroleum industry for accurate data on the viscosity of natural gases, especially at high pressures and high temperatures.

2.6 Other Sources of Viscosity Data

Apart from natural gases, methane is also a component that warrants further investigation. Methane is the biggest constituent of most natural gases, and its concentration increases as the reservoir temperature increases. A review of the literature for measured viscosities of methane, though more encouraging than natural gases, proved the inadequacy of accurate data for methane. Even though the search yielded a few investigations of the viscosities of methane at high pressures, these were carried out at room temperature or below. Most notable of these studies was the work done by van der Gulik, Mostert, and van der Berg[26]. Similarly, there exist a few studies on the viscosity of methane at high temperatures but at atmospheric pressure. However, as in the case of natural gases, no results were founds on the viscosities of methane at high pressures and high temperatures.

Stephan and Lucas[36] put together a compilation of all the available data on viscosity of methane. Most notable amongst these were the data of Huang, Swift, and Kurata[37] and Gonzalez, Bukacek, and Lee[38]. The measured viscosities from these two authors were used to make a table of recommended viscosities of methane at various temperatures and pressures. However even though the temperature range was sufficiently high, the highest pressure tested was only 10000 psia. Fig. 2.26 shows the comparison of methane viscosity as presented in Stephan and Lucas and by the National Institute of Standards and Technology[39].

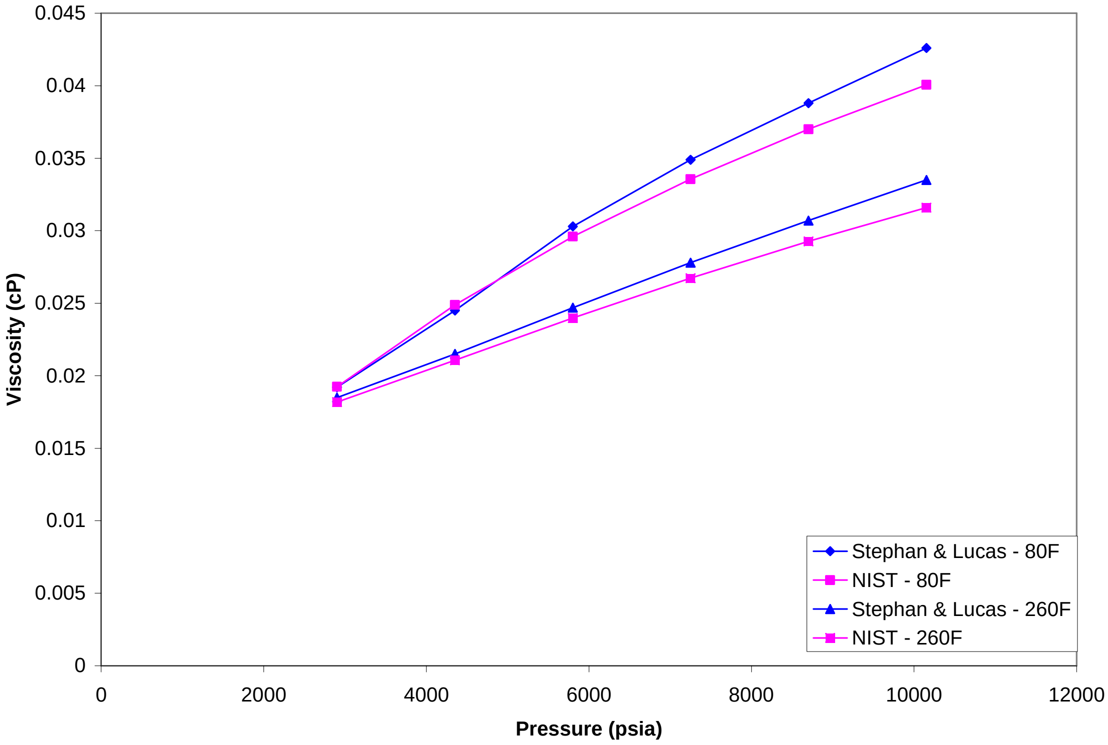

Figure 2.26—Viscosity of methane, Stephan and Lucas[36] and NIST[39]

The figure shows that the viscosity of methane shows a deviation as measured by different authors, even at low pressures.

The National Institute of Standards and Technology (NIST) databank contains some values of the viscosity of methane at pressures even higher than 10000 psia. Fig. 2.27 shows the viscosity of methane for pressures ranging from 5000 to 30000 at 150 °F and 250 °F.

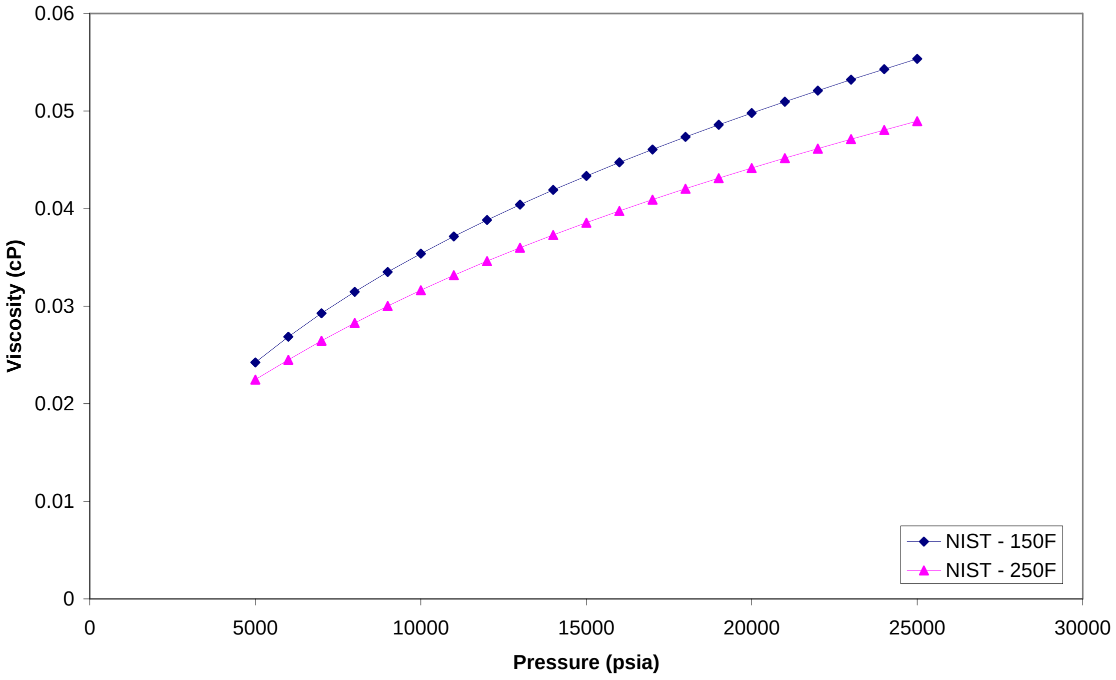

Figure 2.27—Viscosity of methane, NIST[39]

CHAPTER III

METHODOLOGY

In this research, the following tasks were performed, all of which will be described in further detail:

- A thorough review of the literature was performed to determine the best and easiest means for measuring the viscosity of gases.
- A thorough review of the literature was also performed to seek out the most accurate data on viscosities of natural gases, and its largest constituent, methane. During the course of this search, current viscosity prediction correlations were also studied.
- The viscosities of both nitrogen and methane were measured in the laboratory using available viscometers.
- The most accurate viscosity data on methane at high pressure and high temperature were checked using the correlation currently used by the petroleum industry. The specific parameters of the correlation equations were optimized by non-linear regression algorithms using software.

3.1 Review of Literature

A thorough search of the available literature provided us the present and past technologies that have been utilized to measure the viscosities of gases. Some of these techniques were found to be more applicable for high pressure and high temperature measurements than others. More detailed discussion of the various types of viscometers is provided in the previous chapter.

Since one of the objectives of this project was the verification and development of a viscosity prediction correlation, a review of the literature was performed to locate available data on the viscosities of natural gases and methane. The search yielded very few sources of data that satisfied both the pressure and temperature requirements of this project. The most commonly used viscosity prediction correlations were also reviewed. These findings were described in greater detail in the previous chapter.

3.2 Measurement of Viscosity of Gases

Two different types of viscometers were used in this project to try to measure the viscosities of gases at high pressure and high temperature. The primary piece of equipment was a modified falling body viscometer manufactured by Cambridge Viscosity, henceforth referred to as the Cambridge Viscometer. A secondary viscometer was used primarily to check for consistency of data was based on the rolling ball principle. This viscometer was manufactured by RUSKA and will henceforth be referred to as the RUSKA viscometer. Both these viscometers are explained in greater detail below, including calibration procedures, preparation of sample, and operation procedure.

A gas booster system was used to compress the gases to the pressures required in this research.

The gas booster system is a simple equipment consisting of a hydraulic pump coupled with the gas booster cylinder to increase the pressure of a given gas sample. The gas booster system as used in this project was manufactured by High Pressure Equipment Company. Fig. 3.1 shows the schematic of the system supplied by the manufacturer.

The gas booster system is built up of the following important parts.

1. An air operated hydraulic pump which uses house air at a pressure of 70 psia to pump hydraulic oil out of the oil reservoir.
2. The gas booster cylinder which contains a piston to separate the oil and the gas.
3. A set of valves to regulate the flow of sample gas into and out of the system, and to regulate the pressure of the air blowing through the hydraulic pump.

The gas booster system is very functional and performs quite well. The major drawback of the system is that the rate of release of high pressure gas from the system has to be carefully regulated, whereas the outlet valve supplied is inadequate for this measure of control. Similarly, the rate of release of oil from the gas booster cylinder too has to be controlled carefully. An excessively rapid drop in pressure can cause the o-rings in the gas booster cylinder to disintegrate and this can have dangerous implications.

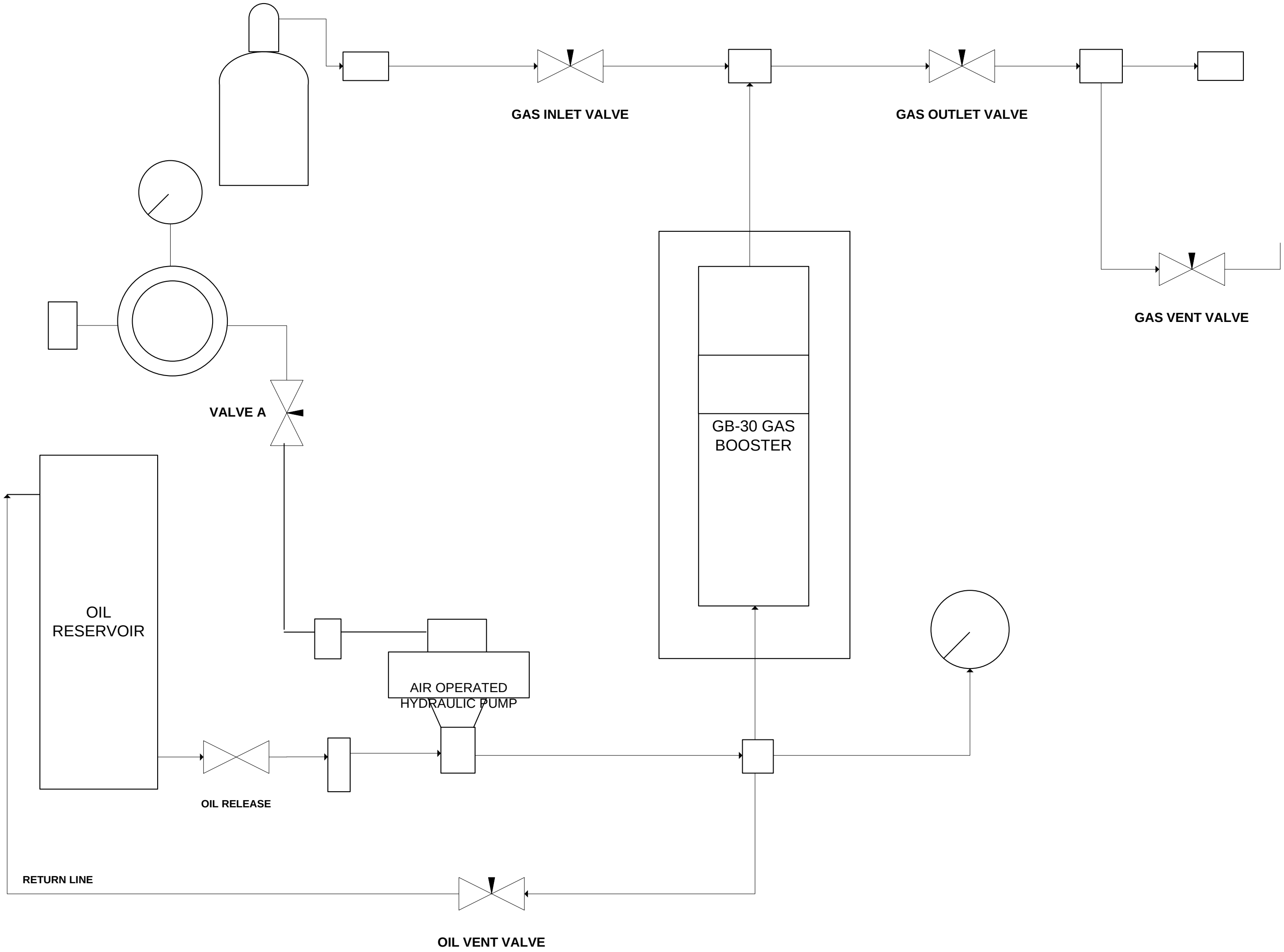

Figure 3.1—Schematic of the gas booster system

In order to improve the system to be more efficient and safe, some changes were made to the gas booster system in the laboratory. An extra pressure transducer was attached to the gas line since the main pressure gauge on the gas booster system was connected to the oil line and this only approximately described the true gas pressure. A couple of micro-tip controlled valves were installed to help in carefully regulating the high pressure gas, and the vented oil.

The high pressure gas from the gas booster system is now available to be used with either viscometer for the measurement of gas viscosity.

3.2.1 Cambridge Viscometer

The principle of operation of the Cambridge Viscometer was explained in the previous chapter. As mentioned before, the system is capable of continuous measurement of viscosity at pressures as high as 25000 psia and temperatures as high as 350 °F. The viscometer was initially supplied in the oil measurement mode, where the measurement chamber is inclined at an angle of 45° from the horizontal. In order to measure the viscosity of gases using the Cambridge viscometer, the measuring chamber had to be aligned horizontally. The Cambridge viscometer was also supplied with RS-232 serial communication support, allowing the data measured by the viscometer to be synchronized with a desktop computer. This gives the provision to save the data for later analysis.

Before the system can be used to measure the viscosity, it has to be calibrated against a known reference standard. The calibration procedure was described in some detail in the previous chapter, the exact procedure is discussed next.

Calibration of the Cambridge viscometer: The Cambridge viscometer is a linear device, and hence the calibration procedure has to be carried out at two different points, the high end of the measurement range, and the low end. A search of the available reference standards pointed to the N.4 standard, a hexane based liquid as the most appropriate fluid to use for the high end calibration. The N.4 reference standard has a viscosity of 0.26 cP at a temperature of 104 °F and atmospheric pressure. The search for a low end calibration fluid failed to provide any fluid which has a viscosity of approximately 0.02 cP at 104 °F and atmospheric pressure. In the absence of any such fluid, nitrogen was used as the low end calibration fluid. Nitrogen has a viscosity of 0.0264 cP at a pressure of 4350 psia and 116 °F. The fact that the low end calibration is carried out at a pressure other than atmospheric causes some non-linearity to come into the system. The effects of pressure on the measurement chamber of the viscometer are accounted for by use of a pressure correction equation. Since the low end calibration requires that the system be under pressure, this equation has to be used during the calibration procedure.

The calibration procedure of the Cambridge Viscometer was as follows.

1. The viscometer is prepared for the injection of N.4 calibration reference standard. This involves changing the input and the output connections to/from the

viscometer. Using an injection syringe, the N.4 fluid is injected into the measurement chamber keeping the outlet valve open. This allows the fluid to flow through the viscometer. After about two system volumes have been injected through the viscometer, the outlet valve and then the inlet valve of the viscometer are closed to isolate the system. The viscometer is turned on and the computer connections made to measure and record the readings. The system is given sufficient time to stabilize both pressure and temperature inside the measurement chamber.

2. Once a consistent reading is obtained from the viscometer, the fluid is purged and some fresh N.4 is filled into the system. After allowing some time for stabilization, the readings are checked for consistency with previous measured values. If the measured viscosity both times is very similar, proceed to the next step, if not, this step is repeated until measurements which are similar or almost similar are obtained.
3. Knowing that the dynamic viscosity of the N.4 fluid at a temperature of 104 °F and atmospheric pressure is 0.26 cP, change the parameters of the viscometer to ensure that the displayed viscosity is 0.26 cP. This finishes the drive level calibration of the viscometer. The calibration can be rechecked by purging out and refilling the viscometer with more N.4 calibration fluid. The measured viscosity should be 0.26 cP or close.
4. Once the drive level calibration has been checked and finalized, the N.4 is removed from the viscometer and modifications are made to the system to enable measurement of gas viscosities. The outlet line of the viscometer is connected to

the exhaust hood. The inlet line of the viscometer is connected to the outlet of the gas booster system. Nitrogen is slowly let into the system taking care to not shock the system by opening the valve completely. A pressure increase rate of around 1000 psia/min is acceptable. Nitrogen is allowed to pass through the system for about 5 – 10 minutes to allow any remaining N.4 to be removed.

5. The outlet and the inlet valves of the viscometer are now closed. The pressure transducer is checked to ensure that the system pressure is 4350 psia. The oven is turned on and set to 116 °F. The system is now allowed to stabilize. Stabilization can take as much as 12 hours when new gas is pumped into the system. During stabilization the viscosity measurements can vary quite a bit.
6. The viscometer should now start to yield some consistent measurements. To ensure consistency of measurements, the gas is purged from the viscometer and fresh gas is injected. After allowing for some time for stabilization, the viscosity is checked against that previously measured. If the two viscosities are consistent, the low end calibration can be carried out. In case the measured viscosities are very different, more time should be given for stabilization, and if this still does not resolve the problem, fresh gas should be used.
7. The low end correction factor is changed such that the measured viscosity of nitrogen at 4350 psia and 116 °F is 0.0264 cP. The total travel time of the piston is also entered through the serial device to complete the low end calibration.
8. The high end calibration is next checked. N.4 is again injected into the system and after allowing some time for stabilization, the measured viscosity is checked against the reference. A little difference is not uncommon, since the low end

correction is used. This difference can be corrected using the high end correction factor. The total travel time of the piston is again entered through the serial device to complete the high end calibration.

9. The viscometer is now calibrated and ready for use.

Both the low end and the high end correction factors are numbers that are entered into the viscometer electronics through the serial communications to dictate how the viscometer measures the viscosity. The procedure described above is the manual calibration procedure. This is preferred over the automatic calibration that can be done using the viscometer electronics, because of greater control over the calibration process.

Measurement of viscosity: The procedure for measurement of the viscosity of gases is similar to the steps used during the low end calibration of the Cambridge viscometer. Using the Cambridge viscometer to measure viscosity requires that the outlet line from the viscometer to be connected to the exhaust hood so that the purged gas can be safely transported out of the laboratory. The gas booster system should already be charged and high pressure gas should be available. The procedure for operating the gas booster system is described in the appendix. The following steps need to be performed to measure the viscosity.

1. The required temperature is set in the oven. This allows the viscometer to be preheated and saves in the stabilization time.
2. The inlet valve to the viscometer is opened. The outlet valve from the gas booster system is opened carefully to slowly fill the system with gas. Care should be

taken to ensure that the pressure does not increase by more than 1000 psi/min. The outlet valve from the viscometer is also opened to allow any impurities remaining in the viscometer to be removed. Once the required pressure has been reached, both the outlet valve and the inlet valve to the viscometer are closed. The outlet valve from the gas booster system is also closed to prevent any pressure to build up in the lines to the viscometer.

3. The viscometer electronics are turned on and the serial communication is started on the computer to measure and record the viscosity. Some stabilization time has to still be given to allow the gas sample to be uniformly heated. The first measurement is usually the most difficult and care should be taken to give enough time for the sample to come to complete equilibrium. The measured viscosity and the pressure corrected viscosity are noted.
4. Some fresh gas is cycled through the viscometer. After some stabilization time, the viscosities are checked for consistency. This step is usually required only at the start of the experiment.
5. If the measurements seem reasonable and consistent, proceed to the next pressure. The inlet valve to the viscometer is opened slowly. There may sometimes be a pressure build-up in the line from the gas booster to the viscometer, and even though the line volume is quite small, the pressure might still increase by almost 3000 psia instantly. If more gas is required the outlet from the gas booster is opened and the pressure is allowed to increase to the next level.
6. The temperature might rise/drop a little because of the new gas, but the volume change is usually so insignificant that temperature stabilization usually occurs

within 5 – 10 minutes. After measuring the viscosity for some time, move forward to the next pressure.

7. This is continued until the last pressure point is reached. After completing the measurement at the final pressure, the oil vent valve on the gas booster system is slowly opened to allow the oil to very slowly trickle back into the oil reservoir. The outlet valve from the viscometer is also opened to allow the gas to slowly leak out of the system. This causes the pressure of the system to drop. The outlet valve should be closed once the penultimate pressure value is reached.
8. Viscosities are usually measured at each pressure point during the pressure increase cycle and then again when the pressure is being released. Measuring twice allows the viscosities to be statistically more consistent. The pressure release using the outlet valve from the viscometer is continued until the starting pressure is reached, stopping at each pressure step to measure the viscosity.
9. Once the viscosity has been measured for all the pressures, the system can be turned off. In order to turn off the system completely, the viscometer electronics have to be switched off, the oven has to be turned off, and the outlet from the viscometer has to be opened to allow the gas to slowly leak to the exhaust hood.

The measurement cycle is now complete. However, the oil usually takes longer to vent back to the reservoir, and this should be allowed at this rate for the reasons described earlier. The measured data is available in a data file for further analysis.

The results of the measurements are shown in the next chapter. During analysis of these results a few important observations were made. The measured viscosities at temperatures higher than the calibration temperature were always lower than the reference viscosities at that temperature. There was no way to actually check if the same was true for temperatures lower than the calibration temperature since calibration was performed at the lowest operating temperature of the system. On further discussions with Cambridge Viscosity it was obvious that a temperature correction similar to the pressure correction would be required.

The Cambridge viscometer was upgraded with new firmware for the temperature correction. Cambridge Viscosity was unable to provide us with the exact equation used since it was proprietary. However, the change to the firmware also changed the outputs coming from the viscometer. The temperature correction was coupled with the existing pressure correction and the results are now collectively referred to as PCV, the pressure compensated viscosities.

Since the viscometer itself was not changed, a new calibration was not required. However, to check that no parameters were modified due to the change in the firmware, calibration was performed. There was no change to the drive speed parameter, however, the low end and the high end correction factors had to be changed a little. A somewhat different approach was taken this time during the recalibration. The N.4 was filled into the system and the measurements were started. The readings were just a little different from what was published in the standard. In order to account for this small difference, the high end correction coefficient and the high end calibration time parameters were changed. The drive level was left at the value which was determined during the original calibration. The system was completely purged and filled with nitrogen for the low end calibration. The low end correction coefficient and the low end calibration time were adjusted to perform the low end calibration. The recalibration was completed by checking the high end calibration by refilling the system with N.4 fluid.

With these done, the viscometer was again ready for gas viscosity measurements. The measurement procedure remained the same for the Cambridge viscometer.

3.2.2 RUSKA Viscometer

The RUSKA viscometer is a simple rolling ball viscometer manufactured by RUSKA equipments. It is capable of measuring viscosities of fluids at pressures up to 10000 psia and temperatures up to 250 °F. The rolling ball viscometer has three predetermined inclination angles for measuring viscosity. The principal of operation was explained in detail in the previous chapter.

Calibration: The RUSKA rolling ball viscometer was calibrated using the N.4 calibration reference standard. The following steps were involved in the calibration of the RUSKA rolling ball viscometer.

1. Clean the balls, barrel, and the inner chamber completely.
2. Check the diameter and the density of the ball. Since the diameter and density of the ball are a critical parameter in the measurement of viscosity using a rolling

ball viscometer, all care should be taken to ensure that both the diameter and the density are accurate.

3. Fill the chamber completely with N.4 calibration fluid and place the ball into the measuring barrel.
4. Run the test at the same temperature as the density and viscosity data is available. In this case the calibration was performed at the following temperatures: 68 °F, 77 °F, 100 °F, and 104 °F. Table 3.1 shows the dynamic viscosity and the density of N.4 calibration standard at these temperatures

Table 3.1—Viscosity and density of N.4 calibration standard

Temperature (°F)	**Viscosity (cP)**	**Density (g/mL)**
68	0.3149	0.6669
77	0.2997	0.6624
100	0.2651	0.6506
104	0.2600	0.6491

5. At each of the above temperatures, run the test using the inclination angles: 45 degrees and 23 degrees. Measure roll-times enough times to obtain statistically consistent values.
6. Multiply the average roll-time in seconds by the density difference of the ball and the fluid.
7. Plot the above product of roll-time and density difference against the viscosity in centipoise on a linear scale.
8. Use the slope of the above line to establish the equation for viscosity.

As already explained before, the determination of viscosity using a rolling ball viscometer is carried out by using the equation

$$\mu = Kt(\rho_b - \rho) \tag{3.1}$$

The calibration procedure on the rolling ball viscometer yields a value of K, the calibration constant. Knowing this calibration constant, the viscosity of unknown fluids can also be measured.

The diameter of the ball used in the rolling ball viscometer was 0.252 inch, and the density of the material was 7.8 g/mL. Table 3.2 presents the roll-times of the ball for various temperatures using the N.4 viscosity calibration standard for the 23 degree inclination angle.

Table 3.2—Calibration of RUSKA viscometer for 23 degree inclination

Temperature (°F)	**Viscosity (cP)**	**Density (g/mL)**	**Density difference, Δρ (g/mL)**	**Roll-time, t (s)**	**Δρ X t (s.g/mL)**
68	0.3149	0.6669	7.131	6.39	45.56709
77	0.2997	0.6624	7.1376	6.12	43.68211
100	0.2651	0.6506	7.1494	5.6	40.03664
104	0.2600	0.6491	7.1509	5.46	39.04391

As explained in the calibration procedure for the rolling ball viscometer, the product of the roll-time of the ball and the density difference between the material of the ball and the sample fluid is plotted against the known viscosity of the fluid. The slope of the line will yield the calibration constant of the viscometer for that particular inclination angle.

Fig. 3.2 shows this graph and the equation of the straight line passing through these points.

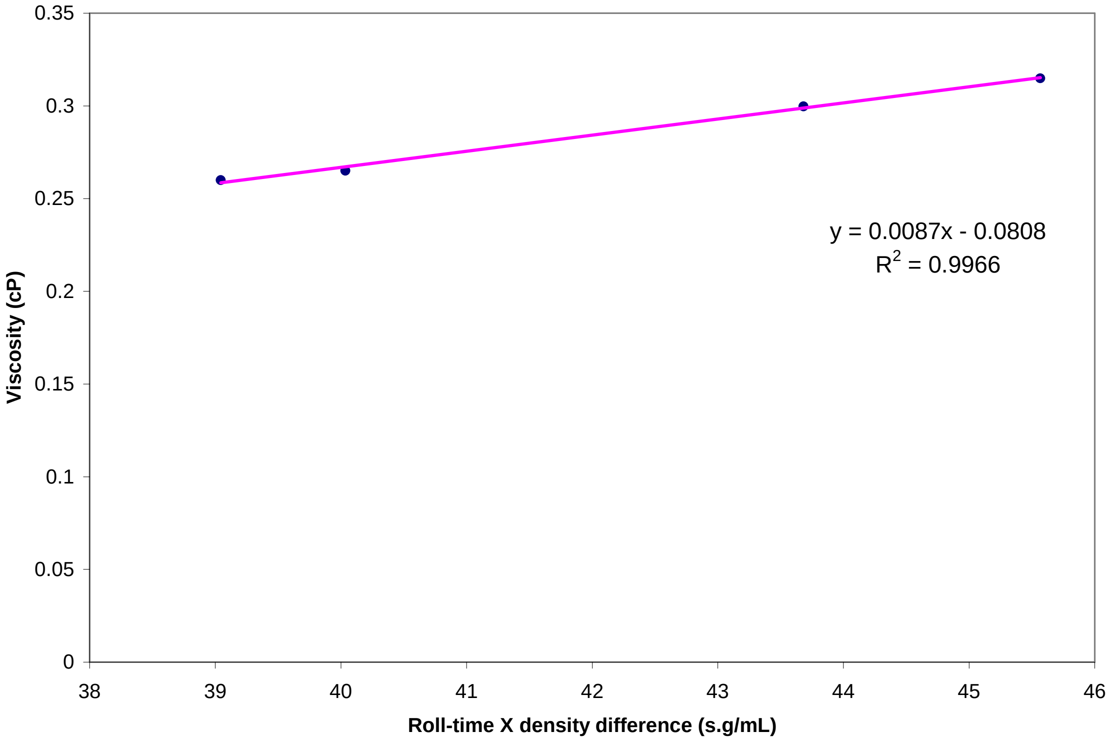

Figure 3.2—Calibration of RUSKA viscometer for 23 degree inclination

The regression coefficient of the points fitted to a straight line is 0.9966 and the value of the calibration coefficient is 0.0087 cP.mL/s/g.

Table 3.3 gives the roll-times for the ball for the 45 degree inclination for the same temperatures measured during the calibration.

Table 3.3—Calibration of RUSKA viscometer for 45 degree inclination

Temperature (°F)	**Viscosity (cP)**	**Density (g/mL)**	**Density difference, Δρ (g/mL)**	**Roll-time , t (s)**	**Δρ X t (s.g/mL)**
68	0.3149	0.6669	7.131	4.16	29.66496
77	0.2997	0.6624	7.1376	4.09	29.192784
100	0.2651	0.6506	7.1494	3.96	28.311624
104	0.2600	0.6491	7.1509	3.95	28.246055

Fig. 3.3 shows the above data plotted in a manner similar to that done for the 45 degree inclination angle.

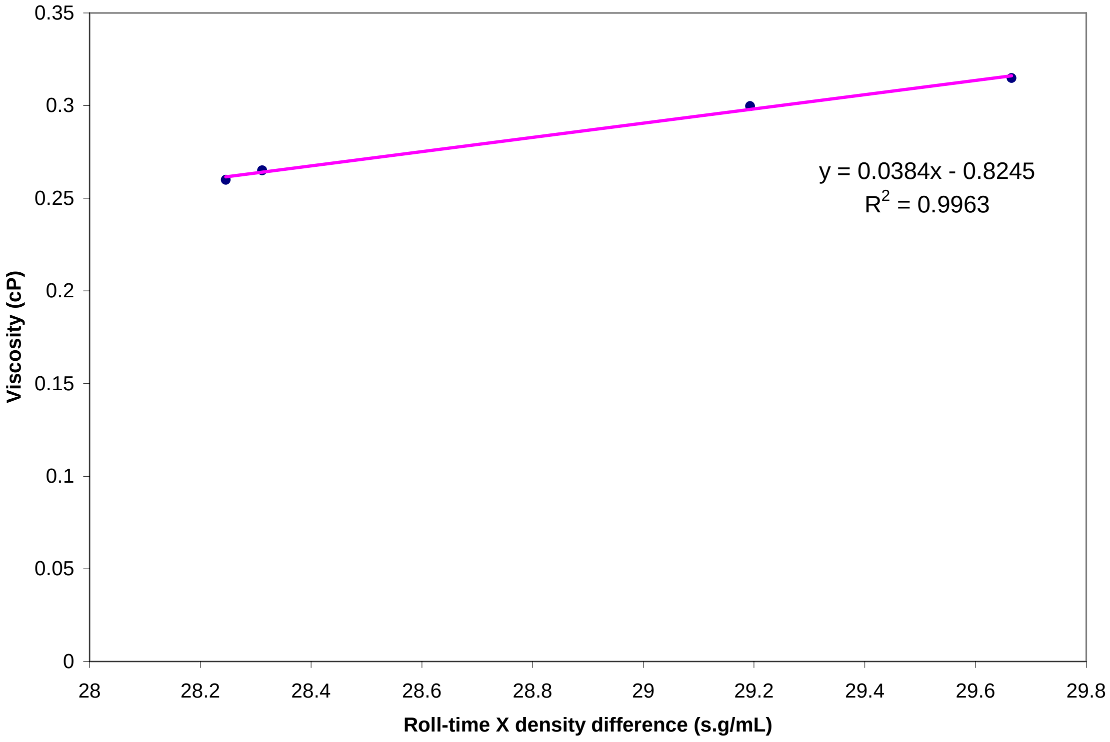

Figure 3.3—Calibration of RUSKA viscometer for 45 degree inclination

The coefficient of regression for the points fit to a linear trend is 0.9963 and the value of the calibration coefficient is 0.0384 cP.mL/s/g.

Measurement of viscosity: With knowledge of the calibration coefficient, and the density of the gas, the viscosity can be calculated by measuring the roll-time on the RUSKA viscometer. Outlined below is the stepwise procedure to be followed for such a test

1. Tabulate the density of the gas at different pressures and temperatures.
2. Thoroughly clean the measuring barrel, the ball and the inside chamber of the viscometer.
3. Tighten the connections on the RUSKA viscometer and connect it to the auxiliary outlet line of the gas booster system. Ensure that there are no leaks in the system.
4. Set the temperature to the desired value.
5. Carefully open the outlet valve on the gas booster system and regulate the pressure on the viscometer. The maximum rated pressure of the RUSKA viscometer is 10000 psia; care should be taken to not exceed this.
6. After allowing the gas and the system to come to equilibrium, incline the rolling ball viscometer to the correct inclination angle and carry out the measurements.
7. Measure the roll-time enough times at each pressure to obtain statistically consistent data.
8. Complete the tabulation of the product of the measured roll-time and the density difference of the ball and the gas.

9. Multiply this product with the calibration coefficient applicable for the particular inclination angle to calculate the viscosity of the gas at the given temperature and pressure.

3.3 Statistical Analysis and Development of the Correlation

The main objectives of this project were two-pronged: measure the viscosity of natural gases at high pressures and high temperatures, and to develop a correlation to predict the viscosity of natural gases for other temperatures and pressures.

During the literature review of available viscosity prediction correlations currently being used by the petroleum industry, we determined the Lee, Gonzalez, and Eakin[34] correlation to be the simplest and the easiest to apply for all problems. Only the density, the molecular weight, and the temperature are required as input parameters for the Lee, Gonzalez, and Eakin correlation to calculate the viscosity.

The only drawback of the Lee, Gonzalez, and Eakin correlation was that since it was based on very limited data and no real high pressure data, it loses all accuracy when applied to high pressures and high temperatures. Sufficient high pressure and high temperature gas viscosity data can then be used to modify and optimize the parameters and coefficients of the Lee, Gonzalez, and Eakin correlation making it suitable for high pressure and high temperature gas viscosity calculations.

Available high pressure and high temperature methane viscosity and density data was compiled from the NIST databank and these were used in the non-linear regression with an aim to retain the functional form of the Lee, Gonzalez, and Eakin correlation. The results of the analysis was the modified Lee, Gonzalez, and Eakin correlation which could, in the absence of actual measured data, be used to calculate the viscosity of methane at high pressures and high temperature with reasonable accuracy. The actual results of this procedure are described in the next chapter.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Results Obtained from the Cambridge Viscometer

The results obtained from the Cambridge viscometer can be divided into two parts – one obtained before the viscometer firmware was upgraded, and the other after the upgrade. We will look at the data chronologically, i.e. we will first start with the data recorded prior to the firmware upgrade. The data measured by the viscometer and recorded on the computer has a structure as shown in table 4.1.

Table 4.1—Data structure of the Cambridge viscometer

Date and Time	Visc. (cP)	TCV. (cP)	Temp. (°F)
•	•	•	•
•	•	•	•

- The date and time is the date and time the measurement was carried out. This can be set either through the viscometer electronics or via serial commands. Even though the viscometer measures continuously, data averaging is done internally and average values are displayed each minute.
- Visc. is the average viscosity as measured by the Cambridge Viscometer. Even though there is provision to measure in one of three units, viscosity units of centipoise (cP) are used in this project. One cP is identical to one mPa s.
- TCV is the temperature compensated viscosity also measured in cP. Temperature compensated viscosity is an estimate of the viscosity that would have been measured if the temperature had been at a reference value which may be different

than the actual temperature. Temperature compensated viscosity is an estimate of the viscosity that would have been measured if the temperature had been at a reference value, other than the actual temperature. This feature was never utilized in this project.

- Temp. is the instantaneous temperature as measured by the RTD on the viscometer. Temperature is measured in degrees Fahrenheit.

The only missing parameter in our analysis now is pressure, which is measured by a pressure transducer connected in parallel with the viscometer. The proximity of the viscometer and the pressure transducer ensures that the pressure measured is accurate and free of any external temperature effects. The pressure gauge connected to the transducer is also capable of transferring data to the computer through a RS-232 serial cable.

Sufficient time for stabilization has to be provided to the system, thus the viscometer measures about thirty readings at the same pressure and temperature level. Micro-sized leaks in the connections cause problems in the maintenance of high pressure in the system. But this pressure loss is still only about 0.2% of the actual pressure. The recorded data is saved on the computer in a tab delimited text file. This file is compatible with Microsoft Excel for further analysis and reporting.

Since there are about 30 values for the same pressure and temperature, these are averaged to give one data point. Presented below are the data points measured using the Cambridge viscometer.

The first test that was carried out after the calibration was a three point test on nitrogen. The viscosity of nitrogen was measured at 116 °F at three different pressures – 4350 psia, 8700 psia, and 13050 psia. The measured viscosity was checked against the reference nitrogen viscosity taken from two sources, Stephan and Lucas, and the National Institute of Science and Technology (NIST) databank. Table 4.2 shows these results.

Table 4.2—Straight line test of nitrogen viscosity

Pressure (psia)	**Viscosity (cP)**		
	Stephan & Lucas[36]	**NIST**[39]	**This work**
4350	0.02641	0.026492	0.025053
8700	0.03675	0.036745	0.036367
13050	0.04725	0.046461	0.045858

The reference viscosities from both Stephan and Lucas and NIST agree very closely at low pressures. However, the viscosities at 13050 are quite different. The NIST data seems to be flattening at higher pressures. The measured viscosity at the lowest pressure, 4350 psia is about 5% lower than the viscosities provided from either Stephan and Lucas or NIST. The difference reduced to 1% at the higher pressures when compared with the NIST data. The viscosity of nitrogen from these three sources is shown in fig. 4.1.

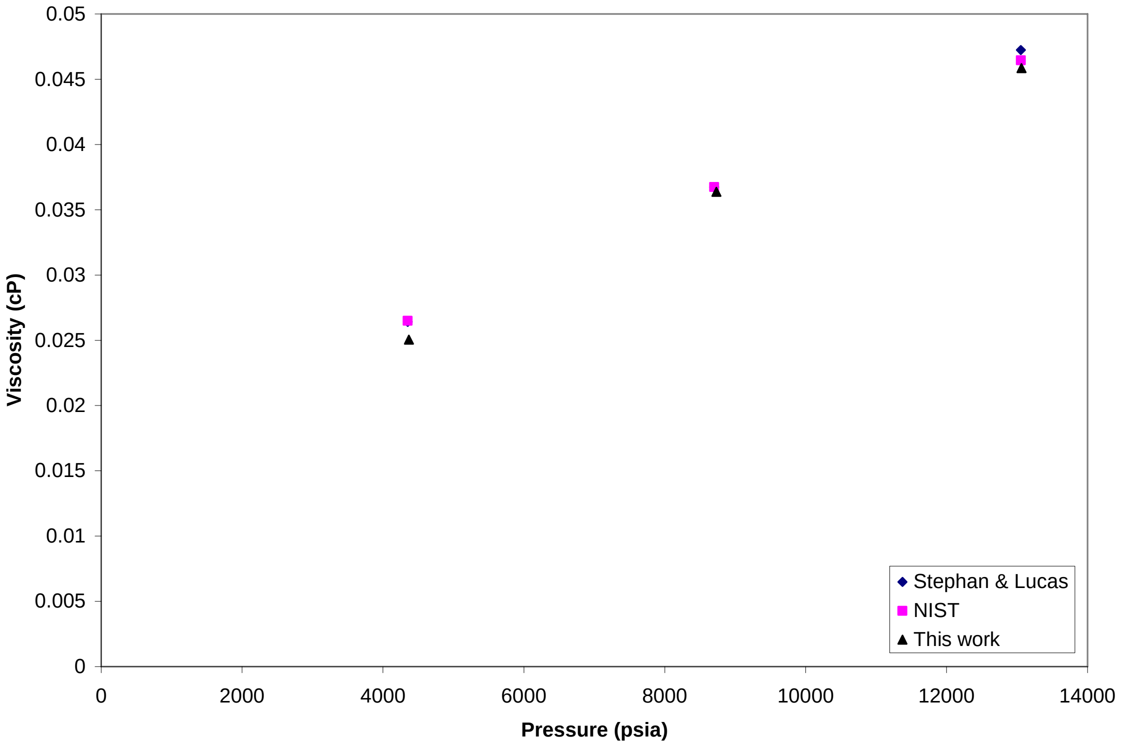

Figure 4.1—Viscosity of nitrogen at 116 °F

After the above test was made on nitrogen, the Cambridge viscometer was used to measure the viscosity of methane. Table 4.3 shows the measured viscosity of methane at 116 °F for pressures from 4350 psia to 20300 psia compared to the viscosity of methane from Stephan and Lucas and NIST. The Stephan and Lucas data only extends up to 10150 psia. Fig. 4.2 shows the viscosities of methane measured by this work compared with the viscosities from the Stephan and Lucas reference. At the lowest pressures the data are reasonably close, having a relative difference of within 3%. As in the case of nitrogen viscosity at 116 °F shown in fig. 4.1, the viscosity of Stephan and Lucas is higher. At 10150 psia, the measured viscosity has a relative difference from the Stephan and Lucas data of almost 5%.

Table 4.3—Viscosity of methane at 116 °F, first run

Pressure (psia)	Viscosity (cP)		
	Stephan & Lucas[36]	**NIST**[39]	**This work**
4350	0.0233	0.023387	0.024118
5800	0.0285	0.02771	0.027923
7250	0.0326	0.031425	0.031515
8700	0.0362	0.034672	0.034927
10150	0.0395	0.037573	0.037514
11600	-	0.040211	0.040137
13050	-	0.042645	0.04252
14500	-	0.044915	0.043786
15950	-	0.047051	0.046192
17400	-	0.049075	0.048236
18850	-	0.051004	0.050421
20300	-	0.052851	0.052581

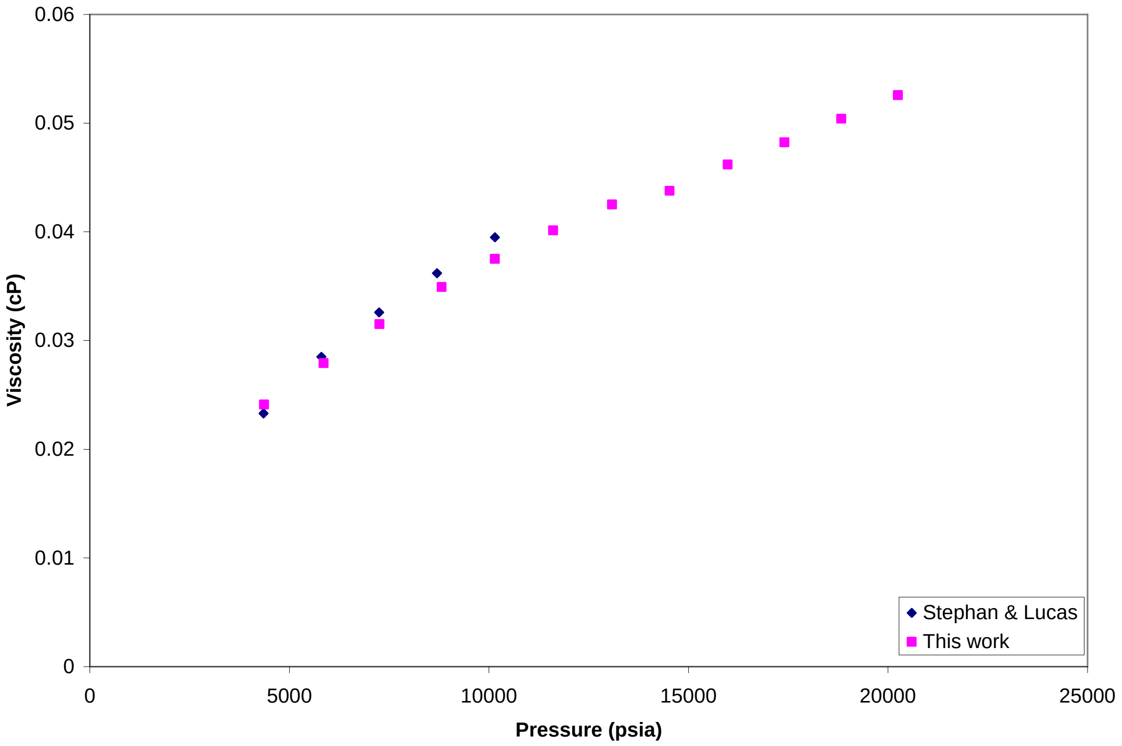

Figure 4.2—Viscosity of methane at 116 °F, first run, compared with Stephan and Lucas

However, to verify the accuracy of the measured viscosities at higher pressure, a comparison with NIST is necessary. Fig. 4.3 shows a comparison of the measured viscosities of methane with NIST reference values. It is clear that the relative differences in this case are much lower than those with Stephan and Lucas.

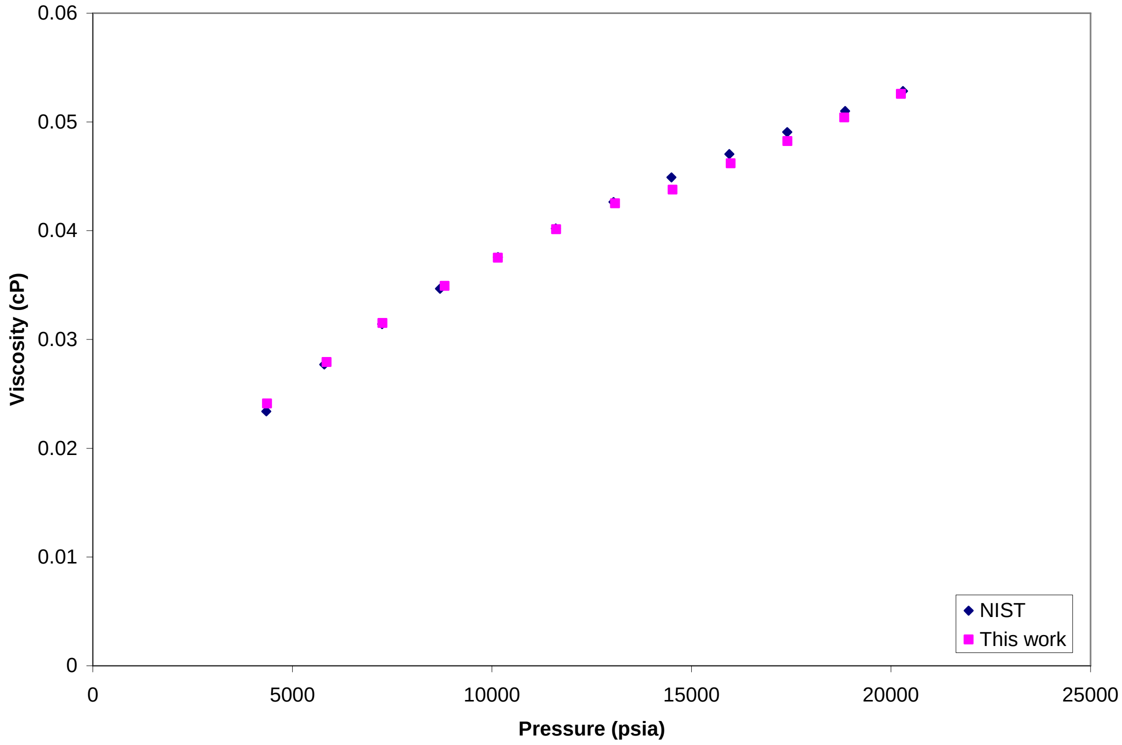

Figure 4.3—Viscosity of methane at 116 °F, first run, compared with NIST[39]

The average relative difference is only 0.3%, with the highest relative difference of 3% occurring at the lowest pressure point.

Next, the viscosity of methane was measured at a temperature of 188 °F. Table 4.4 and fig. 4.4 show the results of this test.

Table 4.4—Viscosity of methane at 188 °F, first run

Pressure (psia)	**Viscosity (cP)**		
	Stephan & Lucas[36]	**NIST[39]**	**This work**
4350	0.0220	0.021706	0.017804
5800	0.0261	0.025257	0.021073
7250	0.0296	0.028469	0.024034
8700	0.0329	0.031348	0.026714
10150	0.0357	0.033948	0.029013
11600	-	0.036323	0.031399
13050	-	0.038515	0.033904
14500	-	0.040556	0.033919
15950	-	0.042473	0.036202
17400	-	0.044285	0.037677
18850	-	0.046007	0.039553
20300	-	0.04765	0.04027

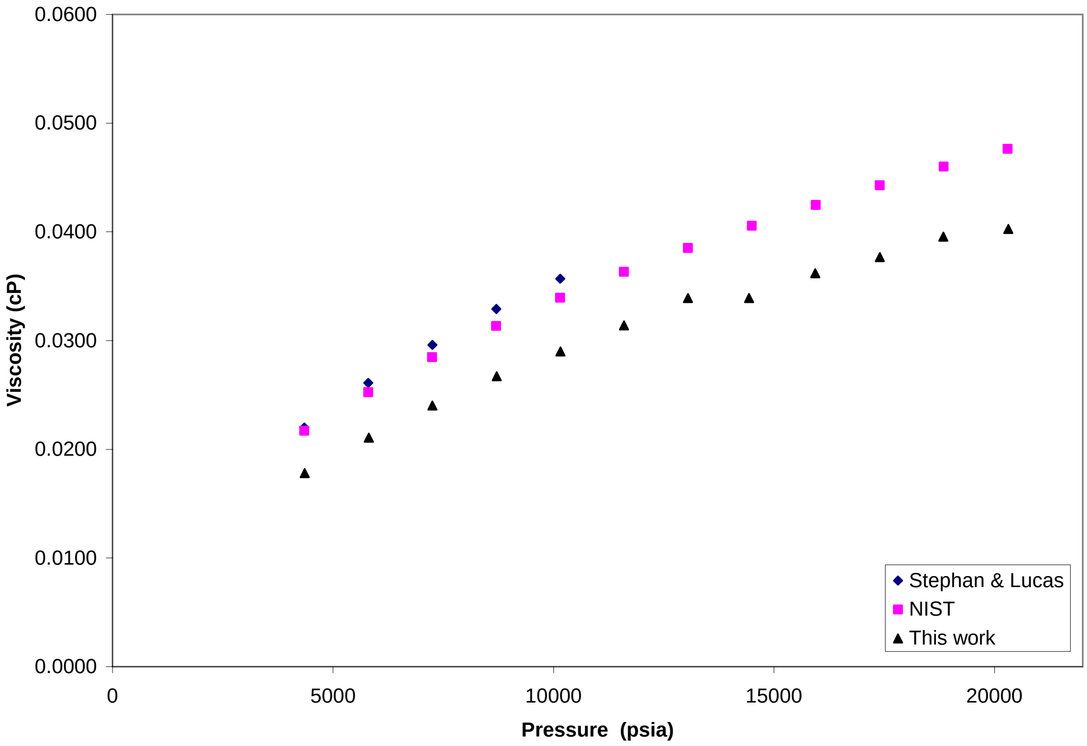

Figure 4.4—Viscosity of methane at 188 °F, first run

It is clearly evident that even though the measured viscosity has the same shape as the reference, the values themselves are incorrect by almost 15%. This may be due to the fact that the measurement temperature and the calibration temperature are different, since the measurements were carried out at 188 °F whereas the actual calibration was done at 116 °F. Even though Cambridge Viscosity had not introduced or used one initially, a temperature correction seems a likely solution to the problem.

The discontinuity in measured viscosity behavior at 14500 psia occurred when the viscometer was left at the same condition for prolonged period of time. It was usually enough to give thirty minutes at the most for stabilization and measurement. Leaving the viscometer at the same pressure overnight has an irreversible effect on the measurements.

This temperature problem gets worse at higher temperatures. Measured viscosities of methane at 260 °F when compared with the reference values of Stephan and Lucas and NIST give average differences of 30% and 25% respectively. However, there was no discontinuity in the measured data this time. Table 4.5 shows the results of this test. The reference viscosities for Stephan and Lucas are again higher than the NIST reference values. Fig. 4.5 shows these data represented graphically. The figure shows that, it seems that if there were some way to linearly translate the data, a better fit could be achieved. But this translation is only possible by recalibrating the viscometer and this would anyway the viscometer useless for any other temperature.

Table 4.5—Viscosity of methane at 260 °F, first run

Pressure (psia)	Viscosity (cP)		
	Stephan & Lucas[36]	**NIST[39]**	**This work**
4350	0.0215	0.021066	0.015253
5800	0.0247	0.023984	0.017373
7250	0.0278	0.026737	0.01939
8700	0.0307	0.029273	0.021484
10150	0.0335	0.0316	0.023319
11600	-	0.033745	0.025037
13050	-	0.035734	0.026458
14500	-	0.037591	0.027804
15950	-	0.039336	0.029307
17400	-	0.040984	0.030771
18850	-	0.042549	0.032039
20300	-	0.044042	0.033194

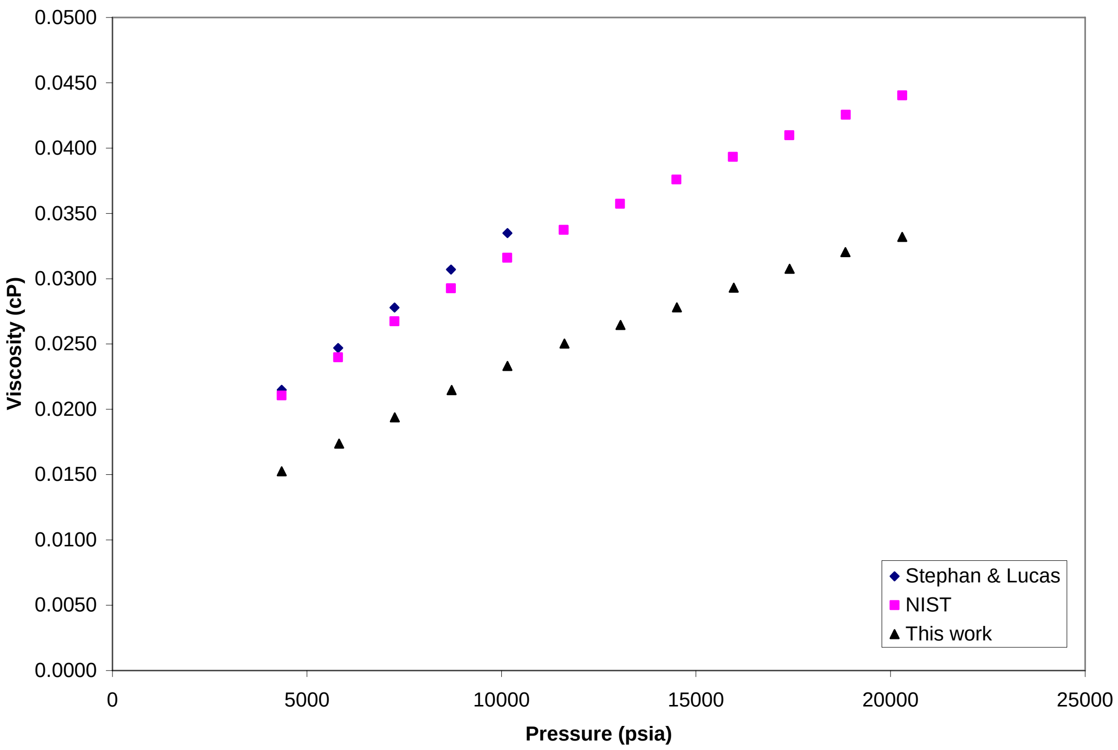

Figure 4.5—Viscosity of methane at 260 °F, first run

A few more tests were done using methane. All the above three temperatures were repeated and in addition two more temperatures were investigated. Methane viscosity at

116 °F is shown in table 4.6 which includes the reference viscosities from NIST, and those measured previously in the first run.

Table 4.6—Viscosity of methane at 116 °F, second run

Pressure (psia)	**Viscosity (cP)**		
	NIST[39]	**This work***	**This work****
4350	0.023387	0.024118	0.024604
5800	0.02771	0.027923	0.028553
7250	0.031425	0.031515	0.032325
8700	0.034672	0.034927	0.035717
10150	0.037573	0.037514	0.038509
11600	0.040211	0.040137	0.041689
13050	0.042645	0.04252	0.044491
14500	0.044915	0.043786	0.046932
15950	0.047051	0.046192	0.049331
17400	0.049075	0.048236	0.051283
18850	0.051004	0.050421	0.053245
20300	0.052851	0.052581	0.05533

* - Viscosity measured during first run

** - Viscosity measured during second run

The viscosity measured this run reads higher than the viscosity that was recorded in the previous run. The average relative difference for this experiment was 4% as compared to the NIST reference data, with the biggest difference of about 5% for the lowest and the highest pressures. Fig. 4.6 shows only the second run and the NIST reference points.

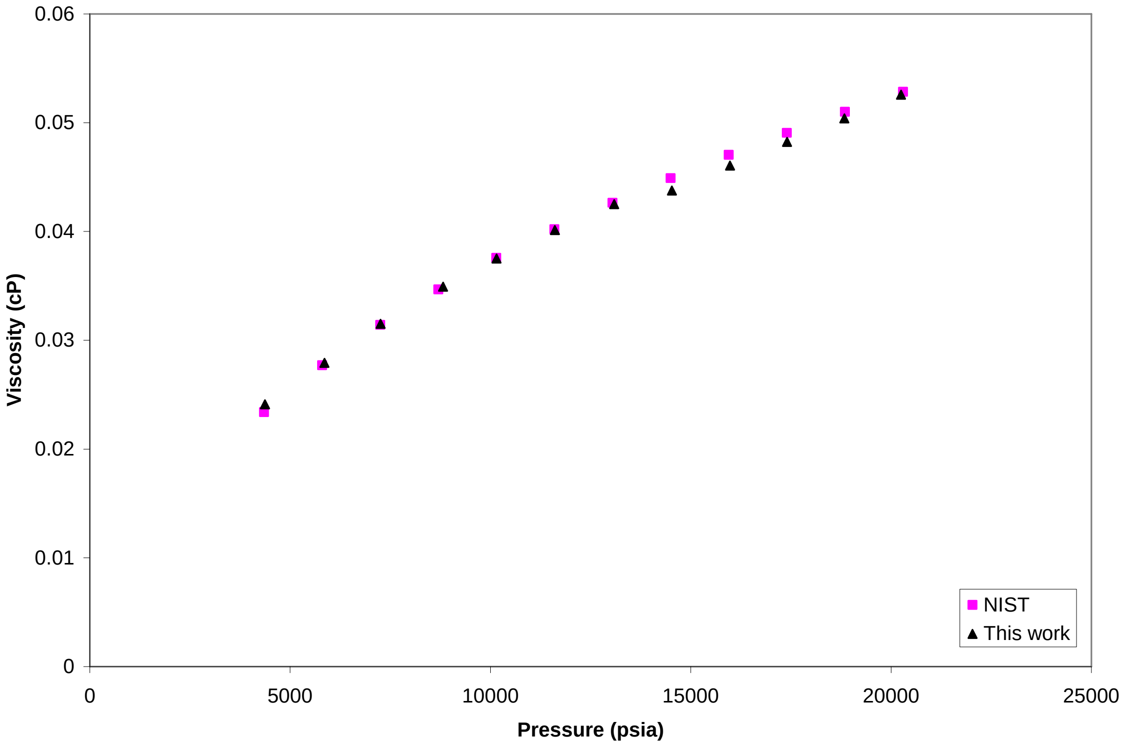

Figure 4.6—Viscosity of methane at 116 °F, second run

The next temperature that was investigated for methane was 152 °F. Table 4.7 shows the measured viscosity of methane at 152 °F for various pressures compared against both Stephan and Lucas and NIST viscosities.

As with other temperatures, the reference values from Stephan and Lucas and NIST are different, especially at higher pressures. The average relative difference of the measured data with the Stephan and Lucas reference is about 12%. The average difference with the NIST reference starts at 10% for 4350 psia, but reduced to about 1% for 20300 psia. The plot of the above data points is shown in fig. 4.7.

Table 4.7—Viscosity of methane at 152 °F, first run

Pressure (psia)	**Viscosity (cP)**		
	Stephan & Lucas[36]	**NIST[39]**	**This work**
4350	0.0225	0.022363	0.019957
5800	0.0271	0.026284	0.023484
7250	0.0309	0.029744	0.026988
8700	0.0343	0.032803	0.030057
10150	0.0373	0.035549	0.032816
11600	-	0.038049	0.035525
13050	-	0.040355	0.037934
14500	-	0.042502	0.04031
15950	-	0.04452	0.042588
17400	-	0.046429	0.044871
18850	-	0.048245	0.047324
20300	-	0.049982	0.049692

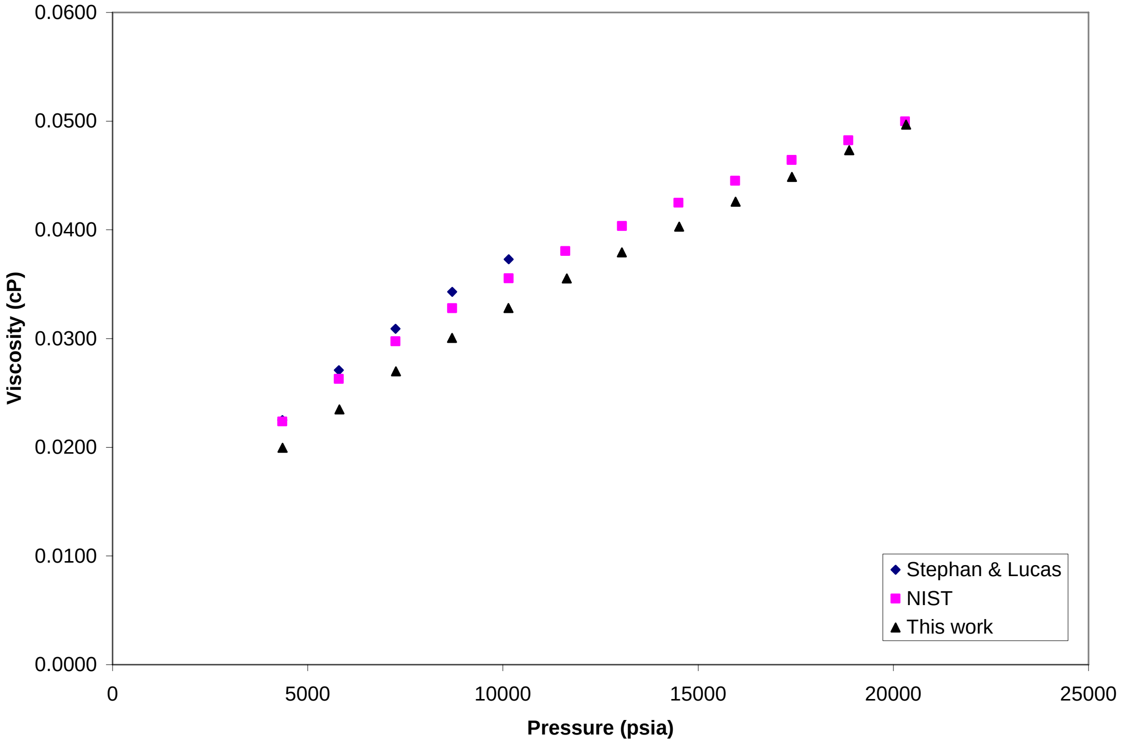

Figure 4.7—Viscosity of methane at 152 °F, first run

The measurement of viscosity of methane at 188 °F was also repeated. Table 4.8 shows the measured viscosities of methane compared to the reference viscosities from NIST and those measured previously. The average relative difference of the measured data with the reference was about 11% with the largest difference again being at a pressure of 4350 psia.

Table 4.8—Viscosity of methane at 188 °F, second run

Pressure (psia)	**Viscosity (cP)**		
	NIST[39]	**This work[*]**	**This work[**]**
4350	0.021706	0.017804	0.018351
5800	0.025257	0.021073	0.021558
7250	0.028469	0.024034	0.024794
8700	0.031348	0.026714	0.02754
10150	0.033948	0.029013	0.029939
11600	0.036323	0.031399	0.032203
13050	0.038515	0.033904	0.034347
14500	0.040556	0.033919	0.036459
15950	0.042473	0.036202	0.038482
17400	0.044285	0.037677	0.040424
18850	0.046007	0.039553	0.042618
20300	0.04765	0.04027	0.044469

[*] - Viscosity measured during first run

[**] - Viscosity measured during second run

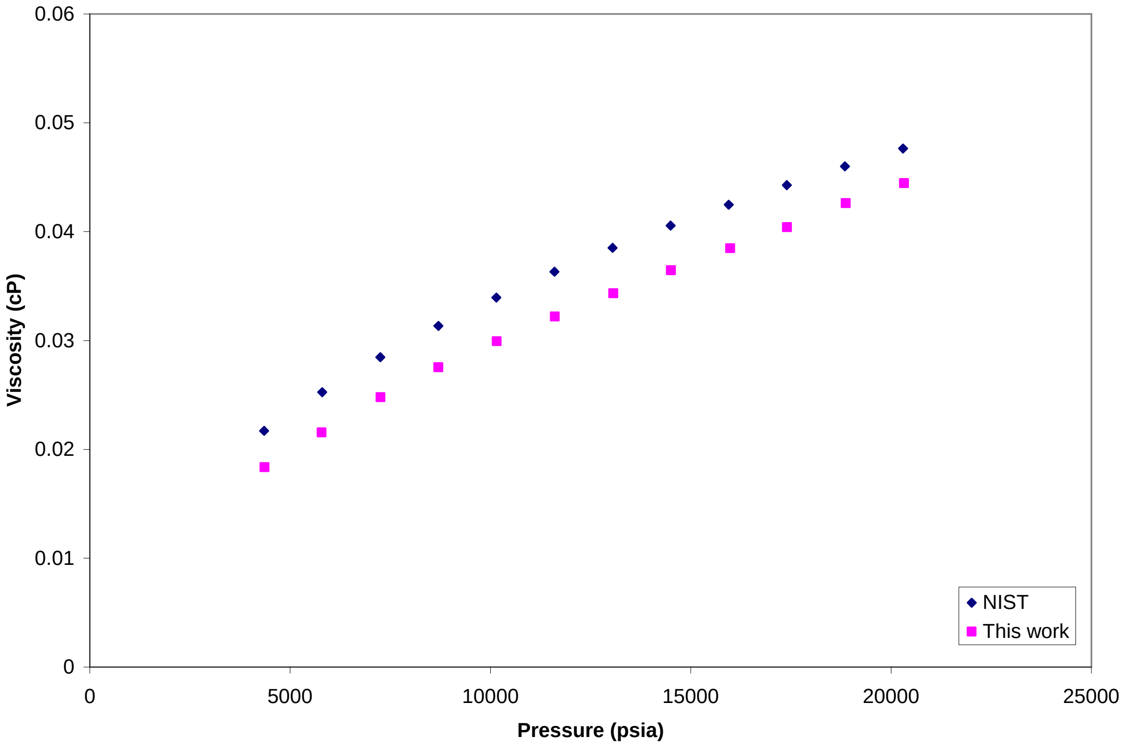

Figure 4.8—Viscosity of methane at 188 °F, second run

Similar results were obtained for the test carried out at 224 °F. Table 4.9 shows the measured viscosity of methane at 224 °F at various pressure from 4350 psia to 20300 psia and compares it with Stephan and Lucas and NIST data. As expected, the average relative differences for this data group are higher than those at lower temperatures. Compared to Stephan and Lucas, the average relative difference is almost 23%. The differences are lower when the data is compared to NIST, but still high at about 18%.

There are again differences in the references with the Stephan and Lucas values being higher than the NIST valves. Fig. 4.9 shows this comparison.

Table 4.9—Viscosity of methane at 224 °F, first run

Pressure (psia)	**Viscosity (cP)**		
	Stephan & Lucas[36]	**NIST**[39]	**This work**
4350	0.0216	0.0213	0.016634
5800	0.0253	0.02452	0.019412
7250	0.0286	0.027498	0.022236
8700	0.0317	0.030204	0.024683
10150	0.0345	0.032667	0.02679
11600	-	0.034925	0.028685
13050	-	0.037013	0.030485
14500	-	0.03896	0.032251
15950	-	0.040788	0.033966
17400	-	0.042515	0.035743
18850	-	0.044154	0.037457
20300	-	0.045719	0.03902

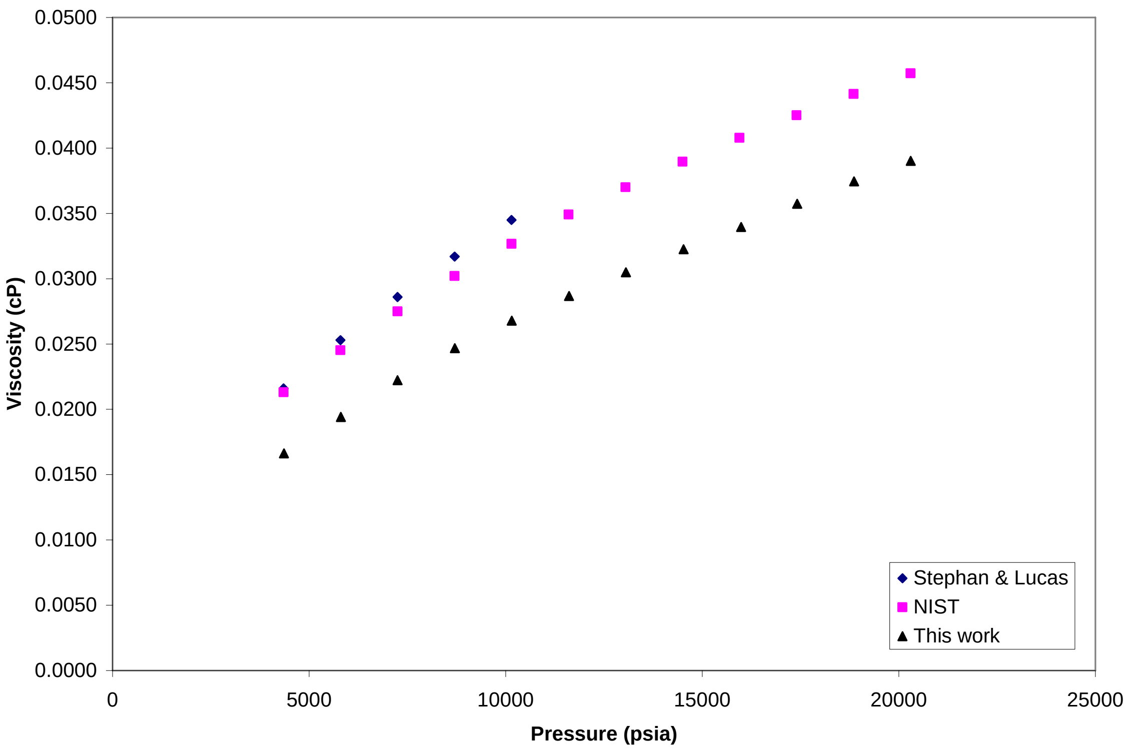

Figure 4.9—Viscosity of methane at 224 °F, first run

We finally repeated the viscosity measurements of methane at 260 °F. Table 4.10 shows these measurements along with the NIST reference values and the data measured previously.

The average relative difference with NIST values is about 23%. The measured and reference points are shown in fig. 4.10.

Table 4.10—Viscosity of methane at 260 °F, second run

Pressure (psia)	**Viscosity (cP)**		
	NIST[39]	**This work[*]**	**This work[**]**
4350	0.021066	0.015253	0.015181
5800	0.023984	0.017373	0.017694
7250	0.026737	0.01939	0.020111
8700	0.029273	0.021484	0.022335
10150	0.0316	0.023319	0.024254
11600	0.033745	0.025037	0.025925
13050	0.035734	0.026458	0.027359
14500	0.037591	0.027804	0.028919
15950	0.039336	0.029307	0.030409
17400	0.040984	0.030771	0.031958
18850	0.042549	0.032039	0.033343
20300	0.044042	0.033194	0.034611

[*] - Viscosity measured during first run

[**] - Viscosity measured during second run

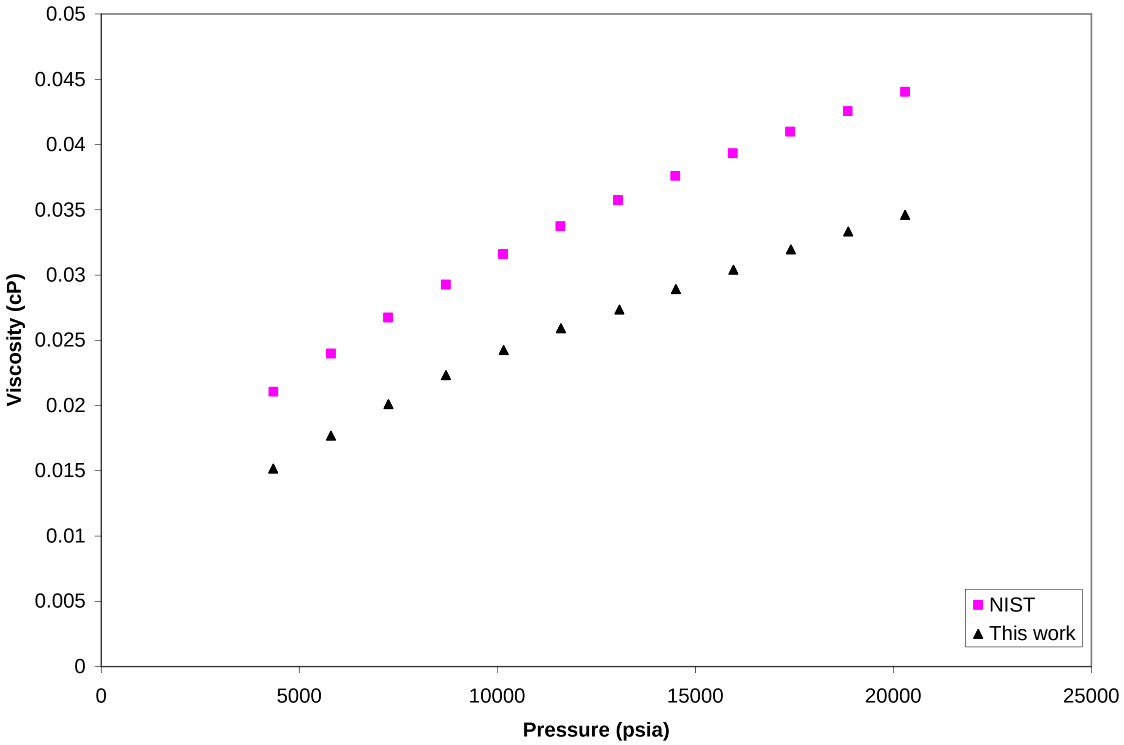

Figure 4.10—Viscosity of methane at 260 °F, second run

Even though the individual figures have been provided for each temperature investigated, it is educational to look at the figure with all the temperatures superimposed on it. However, due to the magnitude of the data points on this graph, the NIST reference points are now represented as lines instead of points. It would still be exceedingly difficult to tell the lines apart due to lack of color. The topmost line is the viscosity at the lowest temperature with temperature increasing downward. This is shown in fig. 4.11.

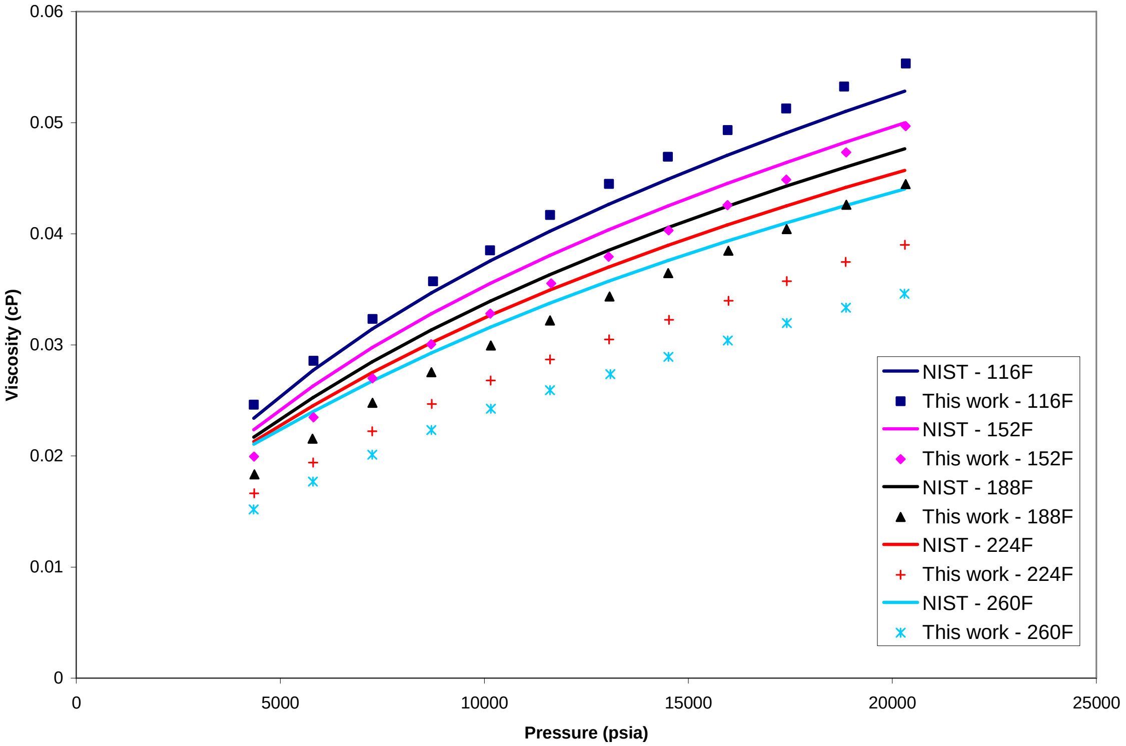

Figure 4.11—Viscosity of methane at five different temperatures

After these tests were performed, the viscometer electronics and firmware were upgraded to include a temperature correction. Data recorded on the viscometer was now transferred to the computer in a slightly different manner. Besides the existing fields discussed earlier in the chapter, the new electronics has the ability to accept pressure values in psia through direct entry or via the serial port using the computer. This pressure is used along with the measured viscosity and the temperature in the internal pressure and temperature compensation equations to give the pressure compensated viscosity (PCV), also measured in cP. Thus the output file contains these two additions, the pressure in psia, and the PCV in cP.

Recalibration of the Cambridge viscometer was carried out after the system upgrade using N.4 viscosity standard, and nitrogen as the high end and low end calibration fluids respectively. Table 4.11 gives the values of the measured viscosity of nitrogen during the recalibration procedure. As before, the viscosity of nitrogen during the calibration was measured at 116 °F.

Table 4.11—Viscosity of nitrogen at 116 °F during recalibration

Pressure (psia)	**Viscosity (cP)**	
	Stephan & Lucas[36]	**This work**
4350	0.02641	0.026516
5800	0.0298	0.030061
7250	0.03328	0.033282
8700	0.03675	0.036231
10150	0.04024	0.039156
11600	0.04374	0.04202875

Fig. 4.12 shows the comparison of Stephan and Lucas and the viscosity of nitrogen measured by the Cambridge viscometer during the recalibration.

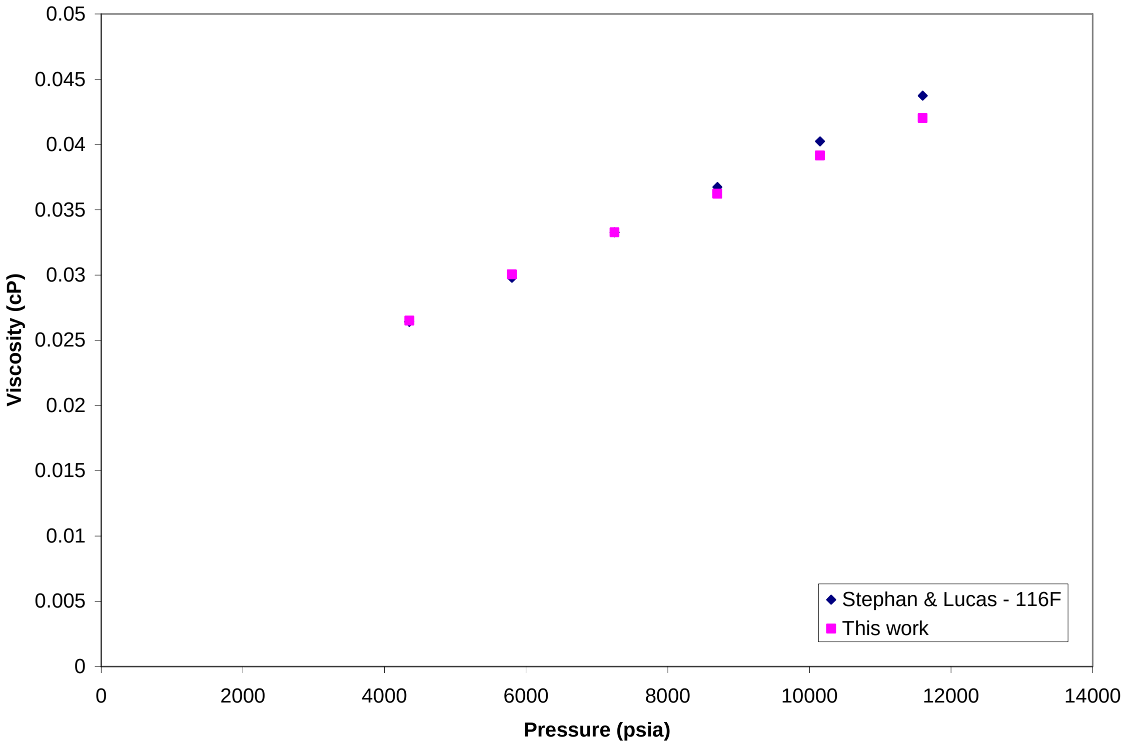

Figure 4.12—Viscosity of nitrogen at 116 °F during recalibration

After recalibrating the system, the viscosity of methane was measured again at 116 °F. Table 4.12 gives these measurements and compares them to the NIST values and also to data measured before the system upgrade, during the first run.

The average relative difference for all the points is about 11%. This is compared to the average relative difference of about 4% when the viscosity was measured before the system upgrade. Even after the re-calibration, all the measurements are lower than the reference. However, the trend of the measured data is as expected. Fig. 4.13 shows this comparison graphically.

Table 4.12—Viscosity of methane at 116 °F, third run

Pressure (psia)	**Viscosity (cP)**		
	NIST[39]	**This work***	**This work****
4350	0.023387	0.024118	0.020689
5800	0.02771	0.027923	0.024946
7250	0.031425	0.031515	0.028024
8700	0.034672	0.034927	0.030755
10150	0.037573	0.037514	0.033119
11600	0.040211	0.040137	0.035336
13050	0.042645	0.04252	0.037303
14500	0.044915	0.043786	0.038977

* - Viscosity measured before system upgrade, during first run

** - Viscosity measured after system upgrade

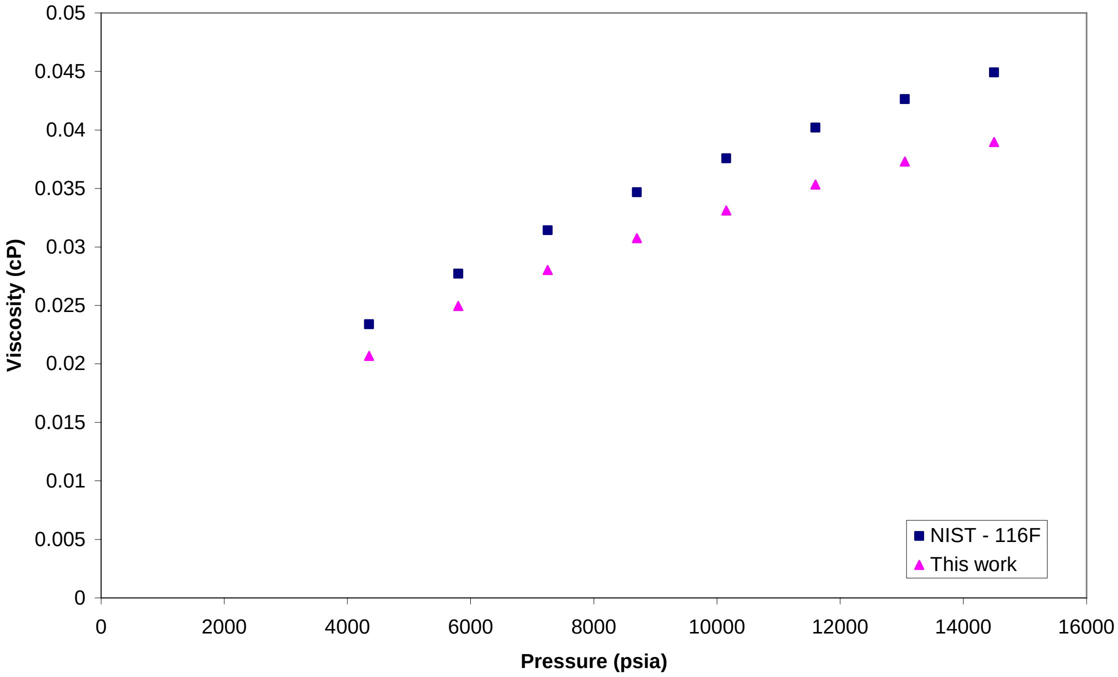

Figure 4.13—Viscosity of methane at 116 °F (after upgrade), third run

The viscosity of methane at 152 °F was measured and the comparison of the measurements with NIST reference data is given in Table 4.13. Even though the average relative difference is only around 3.5%, this is misleading. A better estimate of accuracy and consistency of the measured data is given by the absolute average relative difference which in this case is calculated at about 8%. The maximum relative differences of about 14% each occur for the lowest and the highest pressures respectively.

Table 4.13—Viscosity of methane at 152 °F, second run

Pressure (psia)	**Viscosity (cP)**	
	NIST[39]	**This work**
5800	0.026294	0.03024
7250	0.029756	0.032162
8700	0.032817	0.034646
10150	0.035564	0.036196
11600	0.038065	0.037298
13050	0.040372	0.038128
14500	0.04252	0.040288
15950	0.044539	0.041863
17400	0.046449	0.043305
18850	0.048266	0.044734
20300	0.050003	0.046016
21750	0.051671	0.046816
23200	0.053277	0.047153
24650	0.054828	0.047481

Fig. 4.14 gives a better representation of this problem.

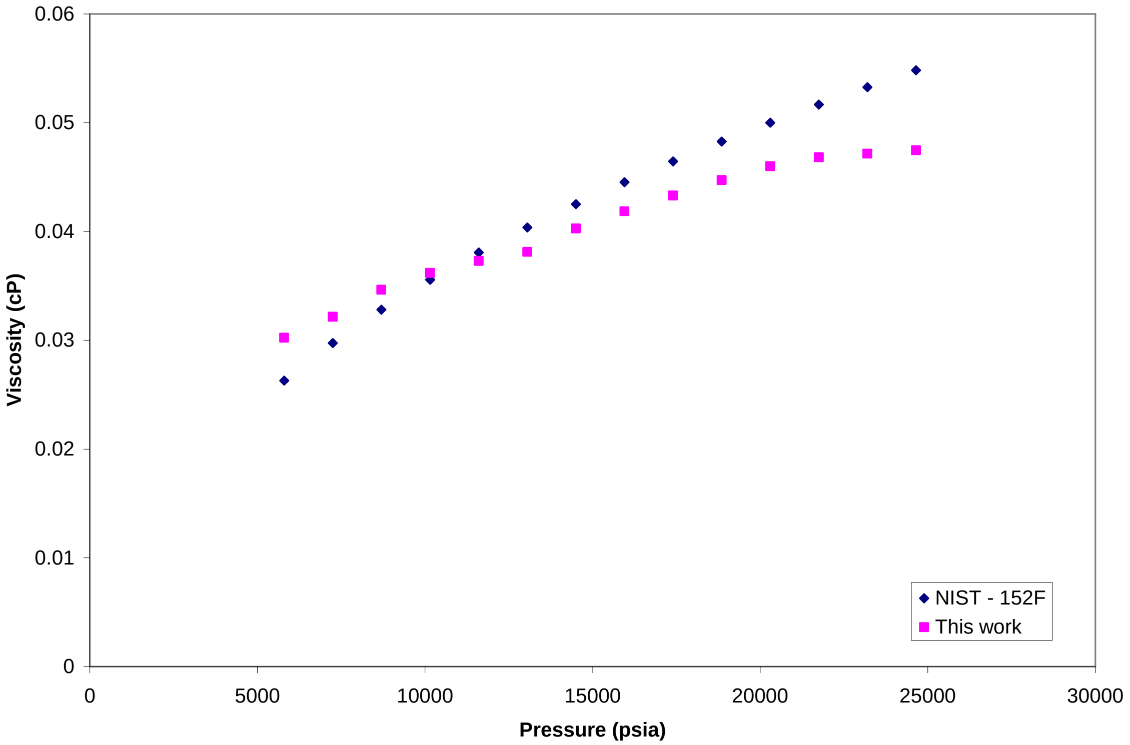

Figure 4.14—Viscosity of methane at 152 °F (after upgrade), second run

Due to the viscosity behavior exhibited in the 152 °F data set, the measurements of methane viscosity were again carried out at 116 °F. The measured viscosities and their comparison with the NIST data and previously measured data are shown in table 4.14. The average relative difference is extremely high at 22%, and the absolute average relative difference is higher still at 24.5%.

Table 4.14—Viscosity of methane at 116 °F, fourth run

Pressure (psia)	**Viscosity (cP)**		
	NIST[39]	**This work[*]**	**This work[**]**
5800	0.02771	0.028523	0.024946
7250	0.031425	0.02968	0.028024
8700	0.034672	0.039621	0.030755
10150	0.037573	0.037177	0.033119
11600	0.040211	0.036181	0.035336
13050	0.042645	0.033601	0.037303
14500	0.044915	0.03044	0.038977
15950	0.047051	0.031012	-
17400	0.049075	0.031922	-
18850	0.051004	0.032699	-
20300	0.052851	0.033423	-
21750	0.054627	0.034213	-
23200	0.056341	0.034949	-
24650	0.058	0.035542	-

[*] - Viscosity measured during fourth run

[**] - Viscosity measured during third run

Fig. 4.15 shows the viscosity of methane measured compared with the viscosity values from the NIST databank.

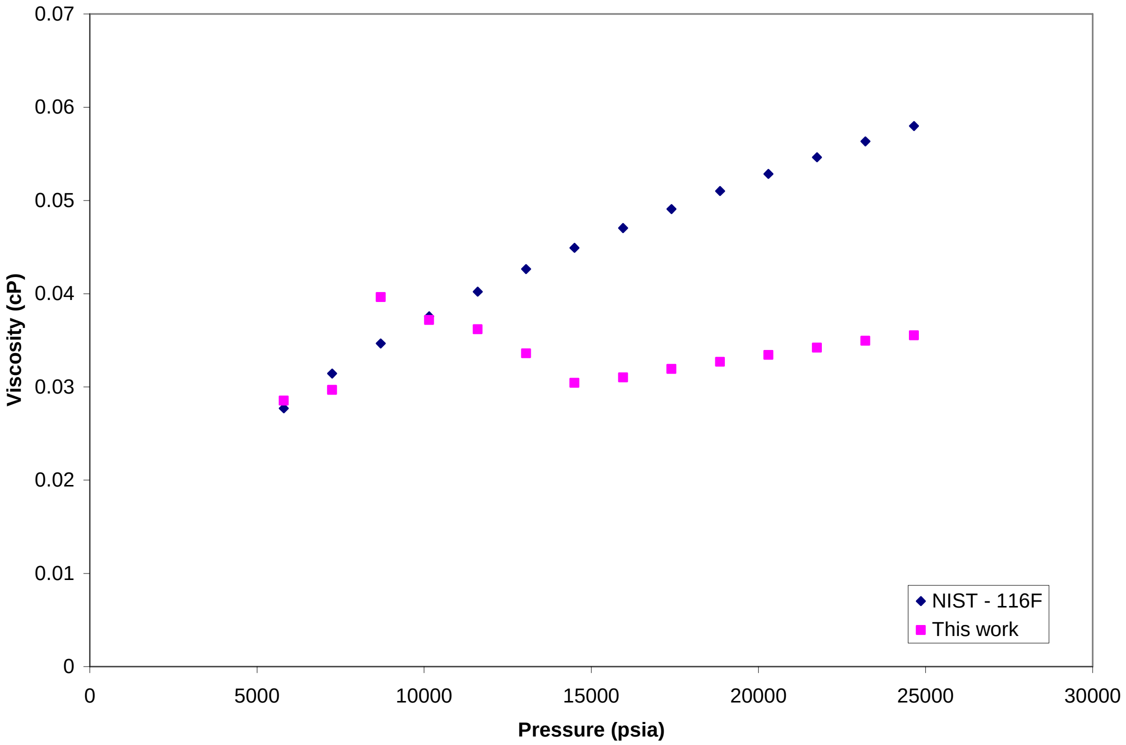

Figure 4.15—Viscosity of methane at 116 °F (after upgrade), fourth run

The reason for this behavior is unknown. To check if this particular test was erroneous or if there is something critically wrong with the viscometer, methane viscosities at 188 °F were measured next. Table 4.15 shows these measurements compared to data from NIST. The average relative difference and the absolute average relative difference are 10 and 29% respectively.

Table 4.15—Viscosity of methane at 188 °F, third run

Pressure (psia)	**Viscosity (cP)**	
	NIST[39]	**This work**
7250	0.028469	0.044916
8700	0.031348	0.043396
10150	0.033948	0.039006
11600	0.036323	0.038863
13050	0.038515	0.036304
14500	0.040556	0.030145
15950	0.042473	0.030406
17400	0.044285	0.031266
18850	0.046007	0.031636
20300	0.04765	0.032655
21750	0.049226	0.033257
23200	0.050742	0.03382
24650	0.052204	0.034097

The above data points are shown in fig. 4.16.

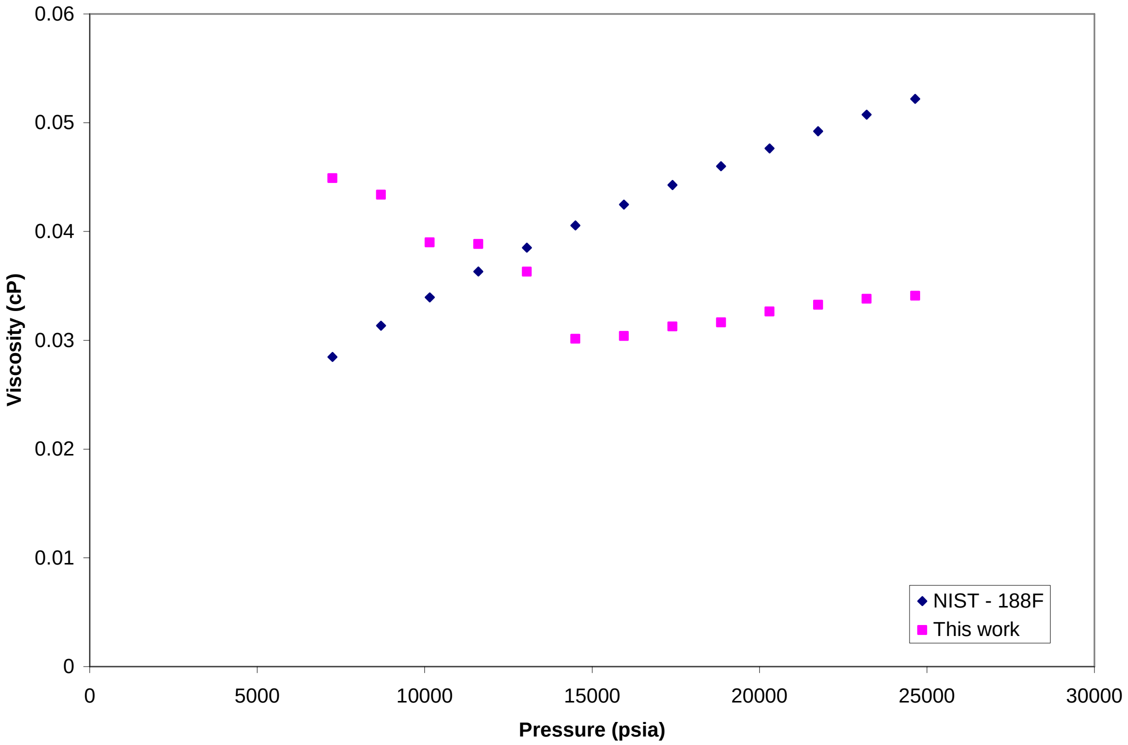

Figure 4.16—Viscosity of methane at 188 °F (after upgrade), third run

It is obvious from the last three tests that after the upgrade of the system, the viscometer is not able to accurately measure the viscosity of gases. The behavior of the viscometer is very strange especially in the pressure range of 5000-12000 psia.

The summary of the results obtained using the Cambridge viscometer is

- The Cambridge viscometer measures the travel time of the piston through the fluid inside the measurement chamber. This measured travel time is converted into viscosity using a proprietary equation.
- At higher pressures, there are mechanical effects induced in the measurement chamber and the piston. To compensate for this change, Cambridge viscosity uses a pressure correction equation.

- The Cambridge viscometer successfully and accurately measures the viscosity of the gas at the same temperature as the calibration temperature. However, on changing the temperature, the accuracy of the measurements is lost. Even though the trend of the measured data follows the behavior as given in the literature, the two curves are parallel.
- Cambridge viscometer with the modified electronics for the temperature and pressure correction for high pressures and high temperatures is unable to offer resolution of the data at pressures between 5000 – 12000 psia.
- In effect, the Cambridge viscometer is only as accurate as the pressure and temperature correction that is used to calculate the actual viscosity knowing the measured viscosity.

There can be many explanations as to the reasons for the viscometer to function improperly. Given below are a few reasons that we propose:

- The low densities of the fluids used in this project. Since this project mainly aimed at measuring the viscosities of gases, and these typically have low densities the viscometer piston has to overcome friction. As the sample pressure increases, the compressibility and the density increase making the behavior more liquid like and hence reducing the friction error.
- The temperature and pressure correction equation used by the Cambridge viscometer is inaccurate. With more available data at higher pressures, the coefficients of the correction equation may be improved to enable the viscometer to measure more accurately.

4.2 Results Obtained from the RUSKA Viscometer

The calibration of the RUSKA rolling ball viscometer was checked by trying to measure the viscosities of nitrogen and methane in the pressure range 6000 – 10000 psia. The procedure for carrying out the measurements has already been outlined in the previous chapter. Since viscosity measurements are being carried out on gases, only the 23 degree inclination angle is used. For higher angles, the roll-time is shortened drastically and nearly identical even for different pressures. Table 4.16 gives the results of the test conducted on nitrogen at a temperature of 116 °F.

Table 4.16—Viscosity of nitrogen at 116 °F using RUSKA viscometer with 23 degree inclination

Pressure (psia)	Density (g/mL)	Roll-time (sec)	Viscosity (cP)
6000	0.34541	3.47	0.225047
7000	0.38081	3.59	0.231724
8000	0.41185	3.745	0.240717
9000	0.43933	3.9	0.249748
10000	0.4639	4.035	0.25753

The viscosity of nitrogen measured here is almost one order off from the reference values. This could be due to turbulence and friction. The original calibration was done using N.4 calibration standard, a hexane based liquid. When measurements are being carried out on gases, the effects of friction and turbulence are much higher, causing the viscometer to yield erroneous results.

Table 4.17 was the measurement of the viscosities of methane at 224 °F. Similar results were obtained as in the case of nitrogen. The measured viscosities were again almost one order greater than the corresponding viscosities in the references.

Table 4.17—Viscosity of methane at 224 °F using RUSKA viscometer with 23 degree inclination

Pressure (psia)	Density (g/mL)	Roll-time (sec)	Viscosity (cP)
8500	0.23428	3.01	0.198124
9000	0.24122	3.06	0.20123
9500	0.24773	3.12	0.204999
10000	0.25385	3.15	0.206802

Both methane and nitrogen viscosities were over-predicted by about the same amount using the calibration coefficient obtained by calibration using N.4. Fig. 4.17 shows these two datasets plotted in the calibration plot.

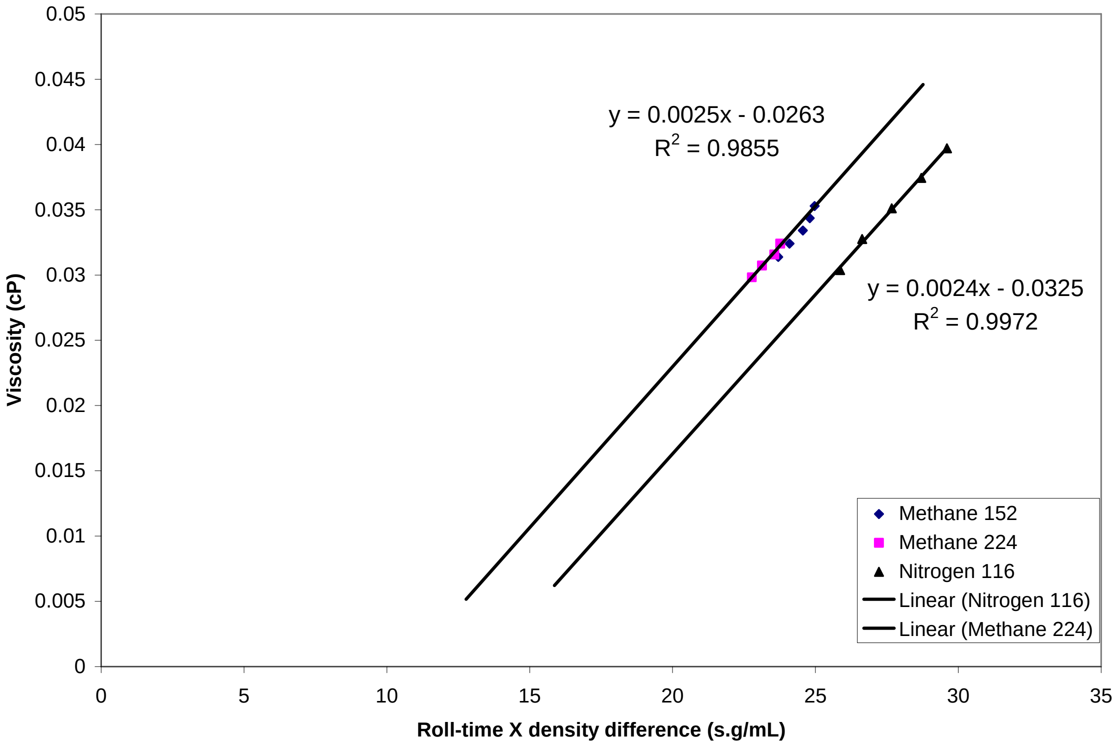

Figure 4.17—Calibration of RUSKA viscometer for gases

It is interesting to note that the trend-lines for both the gases are parallel and hence they have almost similar slopes. The lines are separated due to the different natures of the two gases. The effects of turbulence and friction however, make the viscometer unsuitable for use in its present form. Turbulence and friction affect the measurements of dry gases the most. Sage and Lacey[3] carried out measurements on both lean as well as rich natural gases. Fig. 4.18 shows the measured viscosity of a lean natural gas. It is clear that there exists a large amount of uncertainty in the data. Fig. 4.19 shows the measured viscosity of a rich natural gas. Because of the presence of heavier components, friction does not affect the measurement of viscosities of richer natural gases as much as lean natural gases.

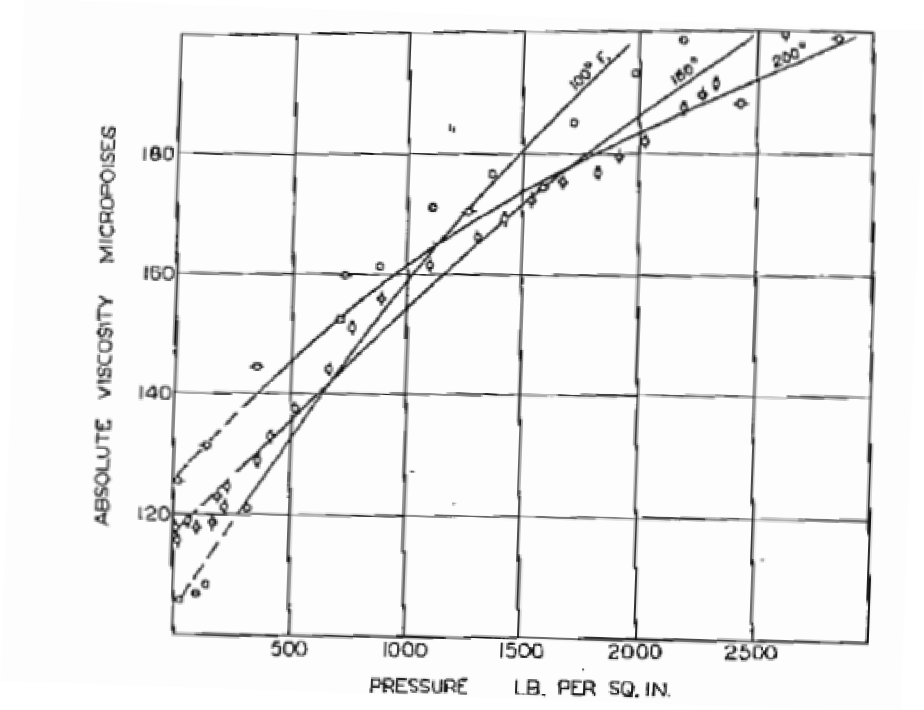

Figure 4.18—Viscosity of lean natural gas, after Sage and Lacey[3]

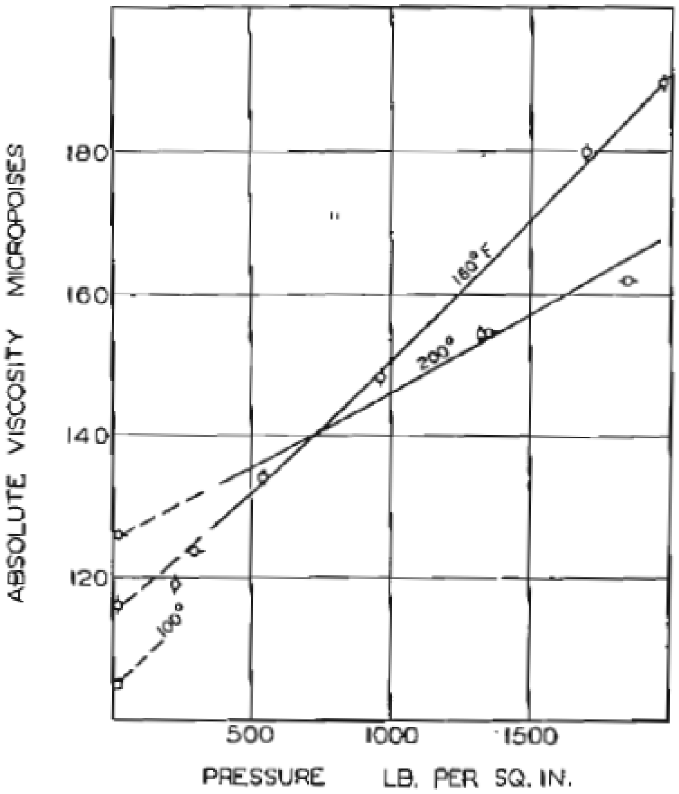

Figure 4.19—Viscosity of rich natural gas, after Sage and Lacey[3]

With modifications to account for the high turbulence and friction, the rolling ball viscometer can be used to measure the viscosities of unknown dry and lean gases, even at high pressures and high temperatures.

4.3 Viscosity Correlation for Pure Methane

Viscosity values for methane at high pressures and high temperatures were obtained from NIST. The pressure range of the data was 5000 – 30000 psia. The temperatures tested were 100 – 400 °F every 50 °F. The total data set consisted of 182 values. The corresponding densities were obtained using the Piper, McCain, and Corredor[40] correlation of the Dranchuk and Abou-Kassem representation of the Standing and Katz z-factor chart.

The procedure for using the Lee, Gonzalez, and Eakin correlation equations for the prediction of gas viscosities was previously explained in chapter II. As explained there, the temperature, density, and the molecular weight are the only parameters required to calculate gas viscosities using the Lee, Gonzalez, and Eakin correlation equations.

The viscosity and density values obtained were used in the Lee, Gonzalez, and Eakin correlation to check its accuracy in predicting the viscosity of methane at high pressures and high temperatures. Table 4.18 shows the results of this analysis.

Table 4.18—Comparison of NIST[39] viscosities with viscosities calculated using the Lee, Gonzalez, and Eakin Correlation

ARE (%)	**AARE (%)**
12.45	12.45

ARE – Average Relative Error calculated as below

$$ARE(\%) = \sum_{i=1}^{N} \left(\frac{y_{i,calculated} - y_{i,measured}}{y_{i,measured}} \right) \times \frac{100}{N} \tag{4.1}$$

AARE – Average Absolute Relative Error calculated as below

$$ARE(\%) = \sum_{i=1}^{N} \left| \frac{y_{i,calculated} - y_{i,measured}}{y_{i,measured}} \right| \times \frac{100}{N} \tag{4.2}$$

The relative errors were the highest for pressures greater than 10000 psia, and temperatures greater than 250 °F. Fig. 4.20 shows the viscosity of methane at 300 °F as referenced by NIST compared to the predicted viscosities of methane at 300 °F by Lee, Gonzalez, and Eakin using the Piper *et al* densities.

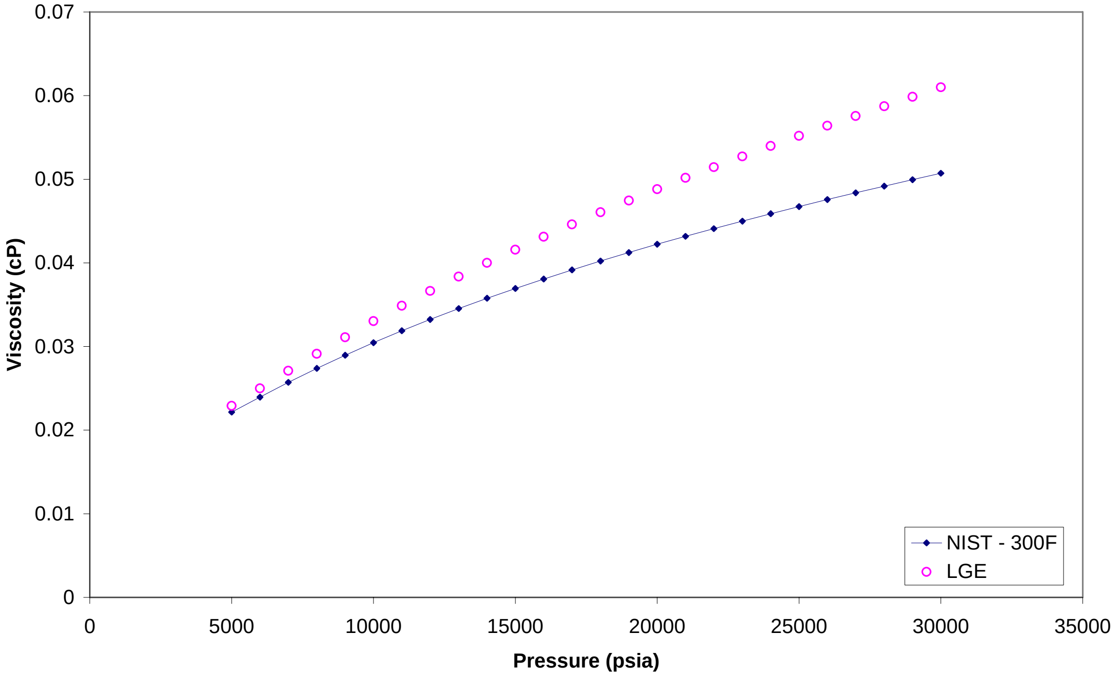

Figure 4.20—Viscosity of methane at 300 °F

The functional form of the Lee, Gonzalez, and Eakin equations was retained during the course of the non-linear regressions. The density and viscosity values for methane at the different temperatures and pressures was regressed to minimize the errors. The result of this iterative procedure is shown below in table 4.19.

Table 4.19—Comparison of NIST[39] viscosities with viscosities calculated using the modified Lee, Gonzalez, and Eakin Correlation

ARE (%)	AARE (%)
-0.002	0.12

The Lee, Gonzalez, and Eakin correlation equations with the changed coefficients are referred to as the modified Lee, Gonzalez, and Eakin correlation. As shown in table 4.19, the new coefficients are very successful in predicting the viscosity of methane at high pressures and high temperatures provided accurate density estimates are known. Fig. 4.21 shows the calculated viscosities using the Lee, Gonzalez, and Eakin equations and the modified Lee, Gonzalez, and Eakin correlation equations compared with the NIST values.

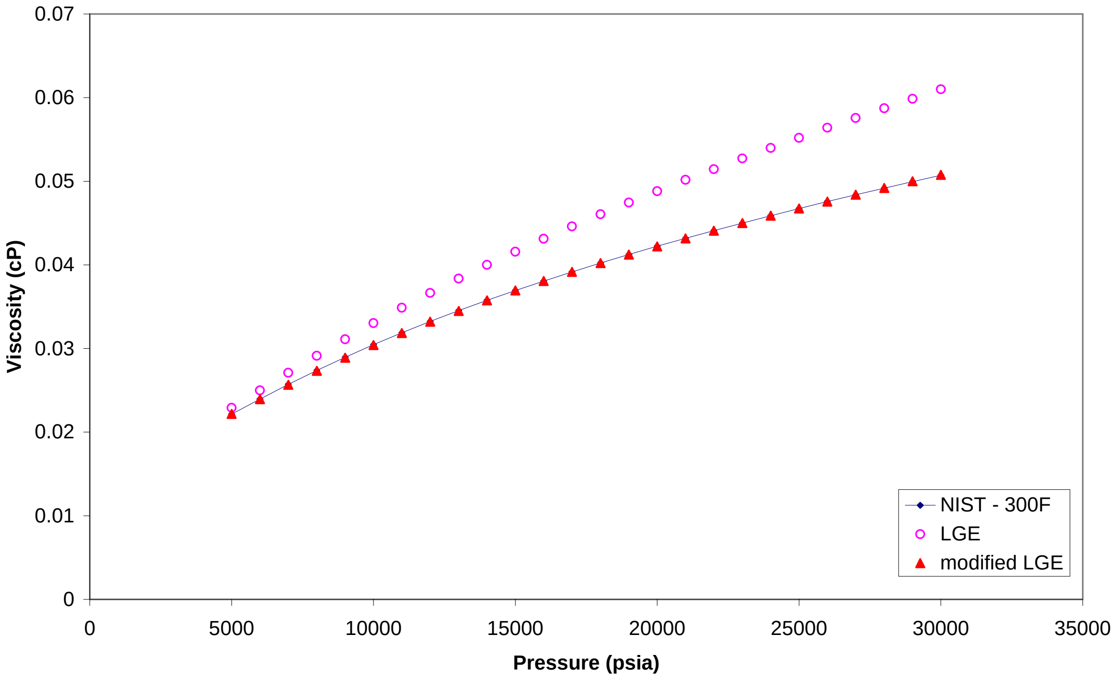

Figure 4.21—Predicted viscosities at 300 °F using the modified Lee, Gonzalez, and Eakin correlation equations

The modified Lee, Gonzalez, and Eakin equations are

$$\mu = K \exp(X\rho^{Y}) \tag{4.3}$$

$$K = \frac{0.0001 \times (5.0512 - 0.2888M)T^{1.832}}{-443.8 + 12.9M + T} \tag{4.4}$$

$$X = -6.1166 + \frac{3084.9437}{T} + 0.3938M \tag{4.5}$$

$$Y = 0.5893 + 0.1563X \tag{4.6}$$

Since the densities of the gases at high pressures and high temperatures are not always available, we have to couple our modified Lee, Gonzalez, and Eakin correlation equations with some density correlation equations to complete the procedure.

Thus we can predict the viscosities of methane at high pressures and high temperature using the Piper, McCain, and Corredor correlation and the modified Lee, Gonzalez, and Eakin correlation with reasonable accuracy.

Gas density can be calculated using the equation below

$$\rho = \frac{pM}{zR(T + 459.67)} \tag{4.7}$$

Since the gas z-factor is the only unknown in the above equation, any method to calculate the gas z-factor at high pressures and high temperatures will enable us to calculate the gas densities at high pressures and high temperatures.

An accurate gas z-factor correlation was developed by Piper, McCain, and Corredor[40]. Their correlation provided a method to calculate the pseudo-reduced pressure and pseudo-reduced temperature which can be used to infer the gas z-factor. The input parameters required for this calculation are mole fractions of the non-hydrocarbon impurities and the gas specific gravity.

The pseudo-reduced pressure and temperature calculated from the Piper, McCain, and Corredor procedure can be used with the Dranchuk, and Abou-Kassem representation of the Standing and Katz chart to provide accurate estimates of the gas compressibility factors.

The NIST databank also provides values of the densities of methane at the different temperatures and pressures investigated in this statistical study. It is instructive to compare the densities calculated using the Piper, McCain, and Corredor correlation with these.

Table 4.20—Comparison of NIST densities with densities calculated using the Piper, McCain, and Corredor[40] Correlation

ARE (%)	**AARE (%)**
-2.19	2.24

The above errors prove the Piper, McCain, and Corredor correlation of the Dranchuk and Abou-Kassem representation of the Standing and Katz z-factor chart to be accurate in predicting gas densities.

In the absence of reliable data on the viscosity of naturally occurring petroleum gases at high pressures and high temperature, the modified Lee, Gonzalez, and Eakin correlation equations along with the Piper, McCain, and Corredor correlation of the Dranchuk and

Abou-Kassem representation of the Standing and Katz z-factor chart can be used with some confidence.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

On the basis of this research, we reached the following conclusions and recommendations for future work:

- There is need for accurate gas viscosity prediction methods. Current gas viscosity prediction correlations are severely limited by data especially at high pressures and high temperatures. Laboratory measured high pressure and high temperature gas viscosity data can help in this problem.
- Commercial gas viscosity measuring devices currently available do not give reliable and repeatable results.
- Current methods of measuring the viscosities of gases suffer from a wide variety of problems including low density of the fluids being measured, and very high friction factor. With modifications to these equipments, gas viscosity can be measured in the laboratory, even at high pressures and high temperatures.
- The National Institute of Science and Technology (NIST) is a useful source of properties of pure gases at high pressures and high temperatures; these can be used in statistical analysis procedures to extend the current correlations. Experimental validation for naturally occurring petroleum mixtures is required.
- In the absence of any reliable data on the viscosity of naturally occurring petroleum gases at high pressures and high temperatures, the modified Lee, Gonzalez, and Eakin correlation can be used with some confidence.

- In the absence of gas density data, the Piper, McCain, and Corredor z-factor correlation along with the Dranchuk, and Abou-Kassem representation of the Standing and Katz chart can be used to predict densities.
- Modify the Cambridge viscometer with a new piping layout design. This will help reduce the dead volume inside the measurement chamber and avoid compressibility effects.
- Test the Cambridge viscometer with new pistons to investigate the friction effects inside the measurement chamber. These friction effects are currently unknown to Cambridge Viscosity Inc.
- Develop a new vertical falling body viscometer using an extension of the existing principle to enable measurements to 40000 psi and 400 °F with inline density measurement.
- Investigate the Vibrating Wire viscometer currently under development by National Institute for Standards and Technology (NIST).

NOMENCLATURE

τ = shear stress, Pa

$\partial u/\partial y$ = velocity gradient, s^{-1}

μ = dynamic viscosity, cP

t = roll or fall time, seconds

K = rolling ball viscometer constant

ρ_b = density of the ball, g/ml

ρ = density of the fluid, g/ml

μ_c = corrected viscosity (Cambridge viscometer), cP

μ_m = measured viscosity (Cambridge viscometer), cP

A = annulus space in thousandth of an inch

P = pressure, psi

Λ = decay constant

ζ = mass per unit length, g/m

ζ' = total hydrodynamic mass of the wire, g/m

a = radius of the wire, m

λ = viscous penetration depth

ω = frequency, Hz

G = gas gravity

x_i = mole fraction of the component in the mixture

T_{ci} = critical temperature of the component in the mixture, °R

p_{ci} = critical pressure of the component in the mixture, psi

T_{pc} = pseudo-critical temperature, °R

p_{pc} = pseudo-critical pressure, psi

x_{C7+} = mole fraction of the heptanes plus fraction

M_{C7+} = molecular weight of the heptanes plus fraction

T_{rj} = reduced temperature of the jth component, °R

T_r = reduced temperature, °R

p_r = reduced pressure, psi

M = molecular weight

T = temperature, °F

z = gas compressibility/ z-factor

R = universal gas constant

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APPENDIX A

Operation of the Gas Booster System

The operation of the Gas booster system is as enumerated below

1. All the valves are initially closed. The cylinder which contains the gas sample is connected to the inlet of the gas booster system and cranked open. The inlet valve in the gas booster system is also opened. All other valves are in the close position. Gas starts to fill in the gas booster cylinder pushing the piston down.
2. The oil vent valve is now opened to allow for any remaining hydraulic oil in the gas booster cylinder to trickle into the oil reservoir. This ensures that the cylinder is now completely filled with the gas sample alone. The gas inlet valve is now closed.
3. Valve A, the master valve for supplying air to the pump is opened and then the air regulator is slowly opened to the desired level. This sets the pump in motion and oil starts coming in from the bottom of the gas booster cylinder. The oil vent valve should now be closed to allow the oil to accumulate in the cylinder.
4. On opening the air regulator further, more and more oil passes into the gas booster cylinder from the oil reservoir. This causes a reduction of volume of the gas sample thus increasing the pressure.
5. When the desired pressure has been reached, both Valve A and the air regulator should be closed so that the pressure does not keep increasing.
6. The gas outlet valve can now be opened to supply high pressure gas as required.

7. When the experiments have ceased, the oil vent valve is now carefully opened to release the oil back into the reservoir. This causes an increase in volume of the gas and causes the pressure to go down.
8. The gas vent valve can now be opened to purge any remaining gas from the system.

APPENDIX B

Table A.1—Density and viscosity values of methane used in development of the correlation, using Piper, McCain, and Corredor[40] and NIST[39]

Temperature (°F)	Pressure (psia)	Density (gm/ml)	Viscosity (cP)
100	5000	0.21813	0.223526
100	6000	0.24064	0.250115
100	7000	0.25866	0.27021
100	8000	0.27358	0.286169
100	9000	0.28628	0.29936
100	10000	0.29733	0.310596
100	11000	0.3071	0.320388
100	12000	0.31587	0.329072
100	13000	0.32382	0.336881
100	14000	0.3311	0.343981
100	15000	0.33781	0.350496
100	16000	0.34405	0.356518
100	17000	0.34988	0.362122
100	18000	0.35534	0.367364
100	19000	0.3605	0.372291
100	20000	0.36537	0.37694
100	21000	0.37	0.381345
100	22000	0.37441	0.385529
100	23000	0.37861	0.389517
100	24000	0.38264	0.393326
100	25000	0.3865	0.396974
100	26000	0.39021	0.400474
100	27000	0.39378	0.403839
100	28000	0.39722	0.407079
100	29000	0.40055	0.410204

Temperature (°F)	Pressure (psia)	Density (gm/ml)	Viscosity (cP)
100	30000	0.40376	0.413223
150	5000	0.19496	0.195768
150	6000	0.21821	0.22294
150	7000	0.23722	0.244568
150	8000	0.25312	0.262133
150	9000	0.26673	0.27677
150	10000	0.27858	0.289259
150	11000	0.28908	0.300126
150	12000	0.29848	0.309738
150	13000	0.307	0.318353
150	14000	0.3148	0.326159
150	15000	0.32197	0.333298
150	16000	0.32863	0.339876
150	17000	0.33484	0.345979
150	18000	0.34066	0.351671
150	19000	0.34613	0.357007
150	20000	0.3513	0.362031
150	21000	0.35621	0.366778
150	22000	0.36087	0.371279
150	23000	0.36532	0.375559
150	24000	0.36957	0.37964
150	25000	0.37364	0.383541
150	26000	0.37755	0.387277
150	27000	0.38131	0.390864
150	28000	0.38493	0.394313
150	29000	0.38842	0.397634
150	30000	0.39179	0.400838
200	5000	0.17595	0.174896
200	6000	0.19907	0.200918

Temperature (°F)	Pressure (psia)	Density (gm/ml)	Viscosity (cP)
200	7000	0.21842	0.222639
200	8000	0.23486	0.240843
200	9000	0.24905	0.256298
200	10000	0.26148	0.269622
200	11000	0.27251	0.281281
200	12000	0.28242	0.29162
200	13000	0.29141	0.300894
200	14000	0.29962	0.309297
200	15000	0.30719	0.316975
200	16000	0.3142	0.324043
200	17000	0.32074	0.330591
200	18000	0.32686	0.33669
200	19000	0.33262	0.342399
200	20000	0.33806	0.347766
200	21000	0.34321	0.35283
200	22000	0.3481	0.357625
200	23000	0.35276	0.362178
200	24000	0.35722	0.366514
200	25000	0.36148	0.370653
200	26000	0.36557	0.374613
200	27000	0.36949	0.378409
200	28000	0.37328	0.382056
200	29000	0.37692	0.385564
200	30000	0.38044	0.388945
250	5000	0.16036	0.158849
250	6000	0.18286	0.183266
250	7000	0.20211	0.204326
250	8000	0.21871	0.222466
250	9000	0.2332	0.23818

Temperature (°F)	Pressure (psia)	Density (gm/ml)	Viscosity (cP)
250	10000	0.24599	0.25192
250	11000	0.25739	0.264057
250	12000	0.26767	0.274888
250	13000	0.277	0.284642
250	14000	0.28555	0.293503
250	15000	0.29343	0.301611
250	16000	0.30074	0.309081
250	17000	0.30756	0.316003
250	18000	0.31394	0.32245
250	19000	0.31994	0.328483
250	20000	0.32561	0.334152
250	21000	0.33097	0.339498
250	22000	0.33606	0.344556
250	23000	0.34092	0.349356
250	24000	0.34555	0.353924
250	25000	0.34998	0.358281
250	26000	0.35423	0.362447
250	27000	0.35831	0.366437
250	28000	0.36224	0.370267
250	29000	0.36602	0.373949
250	30000	0.36968	0.377495
300	5000	0.14748	0.146084
300	6000	0.16912	0.168931
300	7000	0.18798	0.189062
300	8000	0.2045	0.206759
300	9000	0.21906	0.222357
300	10000	0.23202	0.236183
300	11000	0.24364	0.248525
300	12000	0.25416	0.259625

Temperature (°F)	**Pressure (psia)**	**Density (gm/ml)**	**Viscosity (cP)**
300	13000	0.26375	0.269681
300	14000	0.27255	0.278854
300	15000	0.28067	0.287274
300	16000	0.28822	0.295048
300	17000	0.29525	0.302263
300	18000	0.30185	0.308991
300	19000	0.30805	0.315291
300	20000	0.31391	0.321213
300	21000	0.31946	0.326799
300	22000	0.32473	0.332085
300	23000	0.32974	0.3371
300	24000	0.33453	0.341872
300	25000	0.33911	0.346423
300	26000	0.34351	0.350772
300	27000	0.34772	0.354937
300	28000	0.35178	0.358934
300	29000	0.35569	0.362774
300	30000	0.35946	0.366471
350	5000	0.13668	0.135615
350	6000	0.15739	0.157058
350	7000	0.17572	0.176222
350	8000	0.19197	0.193315
350	9000	0.20645	0.208586
350	10000	0.21944	0.222282
350	11000	0.23116	0.234628
350	12000	0.24182	0.245819
350	13000	0.25157	0.256022
350	14000	0.26055	0.265375
350	15000	0.26885	0.273995

Temperature (°F)	Pressure (psia)	Density (gm/ml)	Viscosity (cP)
350	16000	0.27657	0.281978
350	17000	0.28379	0.289405
350	18000	0.29055	0.296343
350	19000	0.29692	0.30285
350	20000	0.30294	0.308973
350	21000	0.30864	0.314754
350	22000	0.31405	0.320227
350	23000	0.31921	0.325424
350	24000	0.32413	0.330369
350	25000	0.32885	0.335086
350	26000	0.33336	0.339595
350	27000	0.3377	0.343912
350	28000	0.34187	0.348055
350	29000	0.34589	0.352036
350	30000	0.34977	0.355868
400	5000	0.12752	0.126818
400	6000	0.1473	0.147034
400	7000	0.16503	0.165279
400	8000	0.18092	0.181725
400	9000	0.19521	0.196571
400	10000	0.20812	0.210011
400	11000	0.21984	0.222227
400	12000	0.23056	0.233381
400	13000	0.24039	0.243611
400	14000	0.24948	0.253038
400	15000	0.2579	0.261761
400	16000	0.26575	0.269869
400	17000	0.2731	0.277433
400	18000	0.28	0.284517

Temperature (°F)	**Pressure (psia)**	**Density (gm/ml)**	**Viscosity (cP)**
400	19000	0.2865	0.291173
400	20000	0.29264	0.297446
400	21000	0.29847	0.303376
400	22000	0.304	0.308997
400	23000	0.30928	0.314338
400	24000	0.31432	0.319425
400	25000	0.31914	0.324279
400	26000	0.32376	0.328922
400	27000	0.3282	0.333369
400	28000	0.33248	0.337637
400	29000	0.33659	0.341739
400	30000	0.34056	0.345688

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