rected to 25°C (77° F) by use of the data of Smith and Brown.[13] There is very good agreement between the extrapolated gas phase atmospheric pressure viscosity and the values available in the literature.[2] The new liquid-phase viscosity data and the Smith and Brown data for propane are plotted in Fig. 9. The data differ by approximately 2 per cent, well within the ± 5 per cent possible error reported by Smith and Brown.

Agreement between the two sets of data in Fig. 9 is very good since they were obtained by two completely different experimental techniques. Smith and Brown in their studies used a rolling-ball viscometer which had to be calibrated with fluids of known viscosity and in the same viscosity and density range as the test fluids. The other instrument was an absolute capillary-tube

TABLE 3—EXPERIMENTAL VISCOSITY DATA OBTAINED WITH THE NEW VISCOMETER FOR PROPANE AND ETHANE AT 25°C (77°F)

Pressure (psia)	Propane viscosity (micropoise)	Ethane viscosity (micropoise)
101	82.2 (v)	—
119	82.6 (v)	—
160	957	—
180	965	—
200	970	94.4 (v)
300	981	—
400	1,004	100.8 (v)
500	1,012	106.2 (v)
533	—	110.1 (v)
600	1,014	—
800	1,049	433.5
1,000	1,075	475.0
1,250	1,111	510.7
1,500	1,139	544.6
1,750	1,168	572.8
2,000	1,204	597.6
2,500	1,252	644.5
3,000	1,297	684.3
3,500	1,352	722.2
4,000	1,406	760.0
5,000	1,483	826.1
6,000	1,578	887.2
7,000	1,664	943.4
8,000	1,754	994.2
9,000	1,840	—

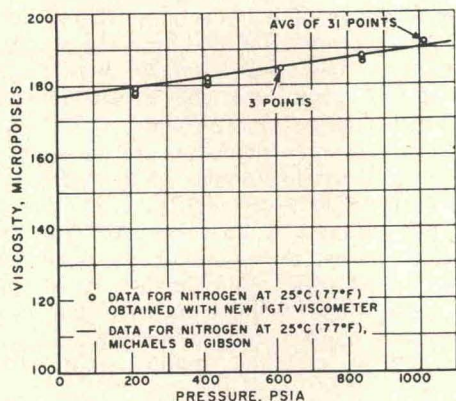(v) = Vapor phase. All other values are for liquid phase.

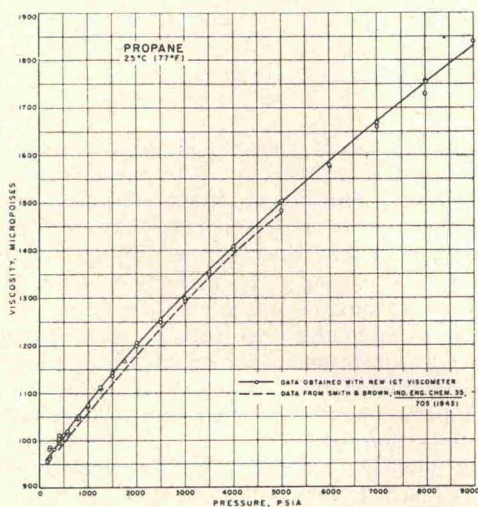FIG. 8—COMPARISON OF NEW VISCOMETER DATA AND LITERATURE DATA FOR NITROGEN.

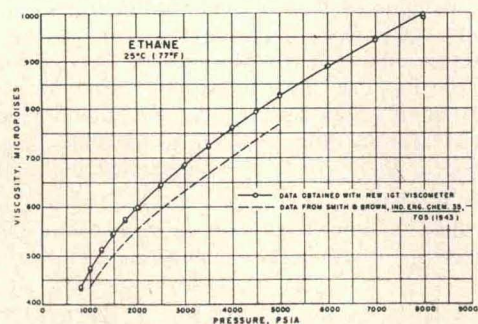FIG. 9—COMPARISON OF NEW VISCOMETER DATA AND LITERATURE DATA FOR PROPANE.

FIG. 10—COMPARISON OF NEW VISCOMETER AND LITERATURE DATA FOR ETHANE.

viscometer, with the viscosity calculated directly from the dimensions of the instrument and flow measurements on the test fluid. That such close agreement exists attests to care and precision of the experimental work by Smith and Brown.

The results for ethane are plotted in Fig. 10, with the ethane viscosity data of Smith and Brown[13] for comparison. Deviations of up to 8 per cent exist between the two sets of data, which is not too unexpected since the viscosity and density relationships for ethane preclude operation of the rolling-ball viscometer under the required conditions of laminar flow. The rolling-ball viscometer was calibrated under conditions of laminar flow, and the ethane measurements were apparently made in the region of turbulent flow. For these reasons it is believed the new viscosity data presented represent an improvement over data previously available.

SUMMARY

An apparatus has been developed for measurement of viscosity of fluids over the range of reservoir pressures and temperatures. Equations have been derived for calculating viscosity from measurement on isothermal, laminar flow of either compressible or incompressible fluids. Viscosity values calculated from experimental measurements on nitrogen and water give excellent agreement with accepted literature data. Viscosity-pressure data obtained for ethane and propane at room temperature indicated significant deviation from existing literature values. It is concluded that an accurate new research tool has been developed for the study of PVT behavior of natural gas, condensate and high-gravity dissolved-gas systems.

NOMENCLATURE*

D = diameter
g_c = dimensionless constant
N = moles of gas
P = pressure
Q = volumetric flow rate
$\overline{u}$ = average velocity
v = volume

V_r = free receiver volume above the electrodes
z = compressibility factor
ε = electrode spacing
θ = time

SUBSCRIPTS:

a = average
D = displaced
f = test fluid
lm = log-mean
m = mercury
t = transition
1 = initial condition
2 = final condition

ACKNOWLEDGMENTS

REFERENCES

1. Bicher, L. B., Jr. and Katz, D. L.: "Viscosities of the Methane-Propane System", *Ind. and Engr. Chem.* (1943) **35**, 754.

2. Carr, N. L.: "Viscosities of Natural Gas Components and Mixtures." *Bull.*, Institute of Gas Technology (June, 1953) No. 23.

3. Carr, N. L., Kobayashi, R. and Burrows, D. B.: "Viscosity of Hydrocarbon Gases Under Pressure", *Trans.* AIME (1954) **201**, 264.

4. Carr, N. L., Parent, J. D. and Peck, R. E.: "Viscosity of Gases and Gas Mixtures at High Pressure", *Chem. Engr. Prog.* Symposium Series (1955) **51**, No. 16, 91.

5. Comings, E. W., Mayland, B. J., and Egly, R. S.: "The Viscosity of Gases at High Pressures", *Bull.* U. of Illinois Engr. Exp. Sta. (1944) 354.

6. Ellington, R. T. and Eakin, B. E.: "A Summary of Methods for Measuring Fluid Viscosities and Compressibilities at High Pressures", *Proc.* National Conf. on Industrial Hydraulics (1957) **11**, 163.

7. Fisher, W. J.: "The Coefficients of Gas Viscosity — II", *Phys. Rev.* (1909) **28**, 73.

8. Golubev, I. F.: "Viscosity of Gases and Gas Mixtures at High Pressure", *Jour Tech. Phys.*, USSR (1938) **8**, 1932.

9. Langhaar, H. L.: "Steady Flow in the Transition Length of a Straight Tube", *Trans.* ASME (1942) **64**, A-55.

10. Michels, A. and Gibson, R. O.: "The Measurement of the Viscosity of Gases at High Pressures—The Viscosity of Nitrogen to 1000 Atmospheres", *Proc.*, Roy. Soc. (1931) **134A**, 288.

11. Rankine, A. O.: "A Simple Viscometer for Gases", *Jour. Sci. Instruments* (1924) **1**, 105.

12. Sage, B. H. and Lacey, W. N.: "Effect of Pressure Upon Viscosity of Methane and Two Natural Gases", *Trans.* AIME (1938) **127**, 118.

13. Smith, A. S. and Brown, G. G.: "Correlating Fluid Viscosity", *Ind. and Engr. Chem.* (1943) **35**, 705.

14. Swindells, J. F., Coe, F. R., Jr. and Godfrey, T. B.: "Absolute Viscosity of Water at 20° C", *Jour. Res.* (1952) **48**, 1.

15. Walters, R. and Eakin, B. E.: "Simplified High-Pressure Electrode Assembly", *Rev. Sci. Instr.* (1957) **28**, 204.

APPENDIX

THEORY OF FLUID FLOW IN THE VISCOMETER

The equation for compressible, steady, isothermal, laminar flow in a capillary,

$$P_1 - P_2 = \frac{2(z_2/z_1)}{(1 + P_2/P_1)} \frac{32\mu\bar{u}L_c}{gD_c^2}, \quad \ldots \quad (2)$$

reduces to the Hagan-Poiseuille equation for incompressible flow,

$$P_1 - P_2 = \frac{32\mu\bar{u}L_c}{gD_c^2} \quad \ldots \ldots \ldots \quad (3)$$

even for gases if operating pressure is substantially above atmospheric. Further consideration of the flow problem required treatment of the pressure drop resulting from the flow of mercury through the composite channel between reservoir and receiver and so-called "end effects". These are normally considered losses due to sudden expansions and contractions in flow channel, such as at the ends of tubes.

The acceleration of a fluid from rest to steady viscous flow requires a certain distance of travel for establishment of final velocity distribution. Until this point is reached the resistance to flow is greater than predicted by Poiseuille's law, as was shown by Langhaar.[9] By applying a linearizing approximation to the Nanier-Stokes equation and defining the transition length, L_t, as the distance required for the centerline fluid velocity to reach 99 per cent of its final value, Langhaar obtained

$$L_t = 0.23r_c(2r_c\bar{u}\rho_f)/\mu \quad \ldots \ldots \ldots \quad (4)$$

For tubes with lengths much greater than L_t, the fundamental equation for the tube-type viscometer becomes,

$$-\Delta P = \frac{8\mu_f QL_c}{g\pi r_c^4} + \frac{\beta Q^2 \rho_f}{g\pi^2 r_c^4} \quad \ldots \ldots \quad (5)$$

in which β is nearly constant at the theoretical value of 1.14 with experimentally determined values from 1.11 to 1.18.[14] The kinetic energy term accounts for full development of a parabolic velocity profile. When true end effects are important the value of β depends upon the flow pattern near the ends of the tubes and the transition from one size to another.

Transition from the large tube to the flow capillary occurs in this instrument in a smooth converging nozzle with a contraction ratio of about 15:1, and at the end of the tube in a similar diverging nozzle. The expansion and contraction processes exactly compensate each other in adiabatic compressible flow, and very nearly so in isothermal, incompressible flow. It is therefore believed that these end effects are negligible for this design.

It is recognized that in this viscometer, some head loss will result from passage of each of the fluids through the elbows in the flow paths. Every effort was made to minimize these losses by providing as few changes in direction as possible and making the flow channels through them as large as possible. Losses in head due to these effects were neglected in developing correction terms.

The final equation representing steady-state flow for the modified Rankine viscometer can be written as follows.

$$-\Delta P = \frac{8\mu_f Q_f L_c}{g\pi r_c^4} + \frac{\beta Q_f^2 \rho_f}{g\pi^2 r_c^4} + \frac{8\mu_m Q_m L_m}{g\pi r_m^4}, \quad (6)$$