Viscosity of Ethane at High Pressures

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The viscosity of ethane was measured with a rotating cylinder viscometer at pressures from atmospheric to 5000 p.s.i.a. Measurements yielded the residual viscosity as a single-valued function of the specific weight even in the critical region. The results are in satisfactory agreement with the measurements of other investigators utilizing widely different types of instruments.

VISCOSITY OF FLUIDS is of significant industrial value from the standpoint of both equipment design and process control. Investigations of the viscosity of ethane have included measurements at atmospheric pressure as a function of temperature by Trautz and Melster (*10*) and Trautz and Sorg (*11*). In addition, Baron, Roof, and Wells (*1*) studied the influence of pressure and temperature upon the viscosity of the gas phase at pressures up to 8000 p.s.i.a. at temperatures between 125° and 275° F. Swift, Lohrenz, and Kurata (*9*) investigated the viscosity of both the saturated liquid and the condensed liquid at pressures up to 700 p.s.i.a. and temperatures between −180° and 90° F. More recently, studies have been carried out over a wide range of pressures and temperatures by Eakin, Starling, Dolan, and Ellington (*8*) in a Rankine-type viscometer.

EQUIPMENT

Unfortunately, there has often been significant deviation in viscosity data obtained by different investigators, particularly when widely different types of instruments have been used. Therefore, a rotating-cylinder viscometer (*4*) was used to study the effect of pressure and temperature upon the viscosity of ethane. No changes in the general arrangement of the equipment were necessary although the lower suspension of the stator was eliminated to decrease the effect of temperature upon the elastic behavior of the suspension. The suspension used was a platinum-tungsten alloy wire 0.0065 inch in diameter and containing 0.10 weight fraction tungsten. The effect of temperature upon the elastic behavior of this alloy has been investigated (*6*). In addition, the torsional elastic constant was independently established with an accuracy of approximately 0.05% by determination of the natural frequency of oscillation of the stator at different temperatures.

To permit a more accurate evaluation of the angular displacement of the stator than was possible with the original equipment, the arrangement shown in Figure 1 was employed. A small shaft which carried an optically flat mirror at its upper end was connected to the housing of the angular transducer. Neither the forces related to the packing nor the torsional moment applied to rotate the angular transducer influenced the measurement of position of the transducer. The angular position could be determined within approximately 2 seconds of arc in an angular displacement of about 6 degrees, giving an accuracy in determining the latter quantity of about 1 part in 5000. Conventional optical techniques involving a telescope and scale were used to establish the angular displacement of the transducer.

The viscosity was calculated by use of the following expression, which involves only the dimensions of the instrument and the elastic characteristics of the suspension:

$$\eta_{T,P} = \left\{ \frac{\phi}{S} \left[\frac{(1/r_1^2) - (1/r_2^2)}{8\pi^2 h} \right] \left[\frac{1}{[1 + \alpha(t - 100]^3 [1 - \{P(1 - 2\lambda)/\epsilon_Y\}]^3} \right] \left[k_{o\theta}\left(\frac{k}{k_o} \right) \right] \right\}_{T,P} \quad (1)$$

The elastic characteristics of the suspension varied slightly with time, apparently as a result of work-hardening in the suspension. The extent of this variation at 100° F. over a period of more than 2 years is shown in Figure 2. It should be recognized that the elastic constant shown in Figure 2 applies to a particular suspension and is not reported in terms of an intensive property of the alloy. This procedure avoided need for a quantitative knowledge of the dimensions of the suspension.

After the first year of use the pertinent dimensions of the rotor and stator did not change with time. The effect of changes in temperature and pressure upon the configuration of the instrument was combined in a single factor k_1. The influence of temperature and time upon the elastic behavior of the suspension was treated in terms of a second factor identified as k_2. Upon this basis Equation 1 may be rewritten

$$\eta_{T,P} = \frac{\phi}{S} [f_1\,(T, P)]\,[f_2(T, \theta)] = \frac{\phi}{S}\, k_1\, k_2 \quad (2)$$

Variation in the configuration factor k_1 of Equation 2 with temperature and pressure is shown in the upper part of Figure 3. Variation in the suspension factor k_2 with temperature and time is depicted in the lower part of the same figure. It is emphasized that the coefficient in the upper part of Figure 3 is based upon direct measurement of dimensions of the instrument and the predicted effect of temperature and pressure on these dimensions. The influence of temperature and time upon the elastic properties of the suspension shown in the lower part of Figure 3 was also determined by direct measurement. The influence of temperature alone on the behavior of the suspension was in excellent agreement with the independent determinations of Rode (*6*). The coefficients have been evaluated with sufficient precision that they are known with an uncertainty of 0.001 fraction.

Hilsenrath (*2*) carefully reviewed the data on the viscosity of helium at atmospheric pressure, which is apparently known with an uncertainty of the order of 0.2%. The viscosity of helium, which was measured with the rotating-cylinder viscometer at atmospheric pressure, is compared to the values reported by Hilsenrath (*2*) and Kestin (*3*) and shown as a function of temperature in Figure 4. Data from the rotating-cylinder instrument were obtained over a period of nearly 2 years, and illustrate the stability of this type of viscometer with respect to

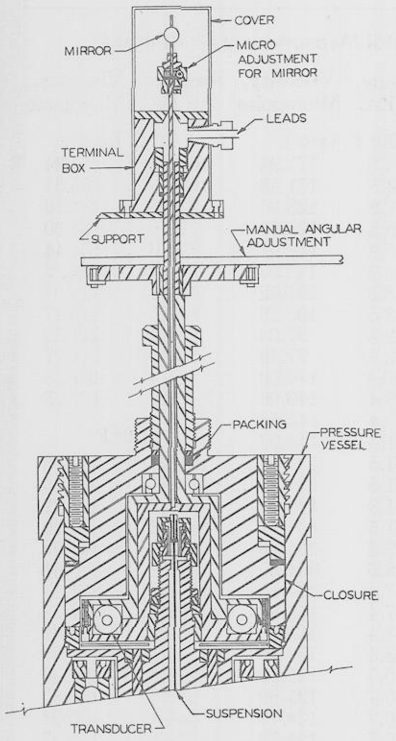

Figure 1. Arrangement for measurement of angular position of transducer

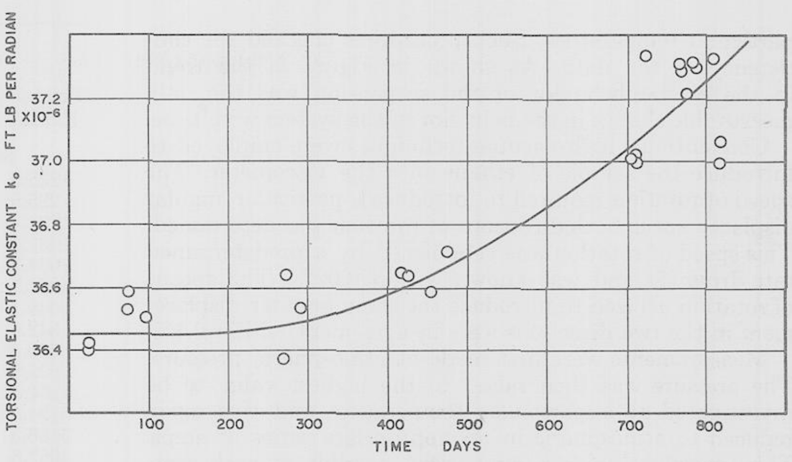

Figure 2. Variation in elastic properties of suspension with time

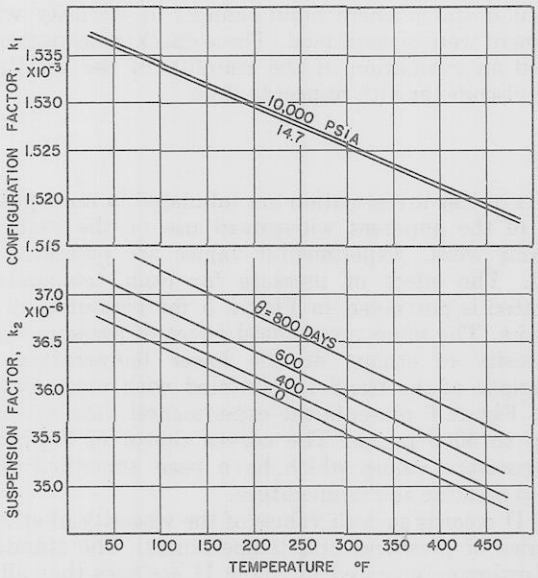

Figure 3. Effect of pressure, time, and temperature upon characteristics of viscometer

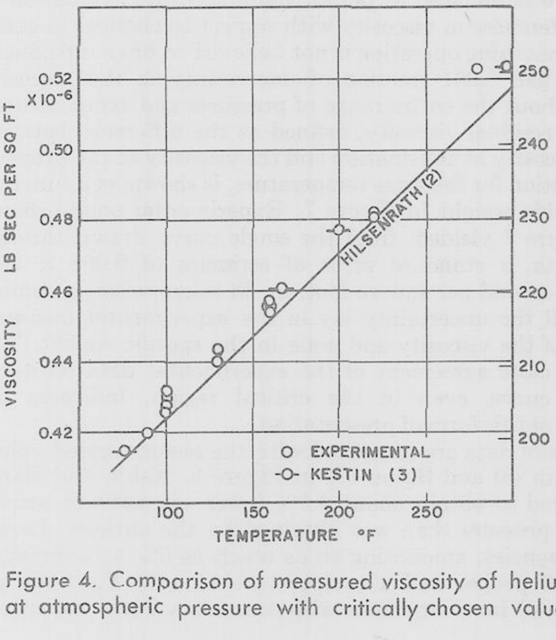

Figure 4. Comparison of measured viscosity of helium at atmospheric pressure with critically chosen values

time when the effects of temperature and pressure shown in Figures 2 and 3 are taken into account.

As a result of the satisfactory agreement between the experimentally measured values of the viscosity of helium and those reported by Hilsenrath (2), the viscosities reported for ethane were based upon the measured characteristics of the instrument. Therefore, the results represent independently established values and are not in any way related to the available data concerning the viscosity of helium or other gases. The information submitted in Figures 2 and 3 was known with sufficient accuracy to yield a probable error of not more than 0.25% in the established characteristics of the instrument. Except in the immediate vicinity of the critical state, where rapid changes of the viscosity with variation in pressure and temperature were encountered, the reported values of the viscosity for ethane should not involve uncertainties larger than 0.5%.

MATERIALS

The helium (Air Reduction Pacific Co.) used for the comparison shown in Figure 4 was reported to contain less than 0.0003 mole fraction of material other than helium. The purity was confirmed by mass spectrographic analysis. The ethane (Phillips Petroleum Co.) was research grade and was reported to contain less than 0.001 mole fraction of material other than ethane. Measurements of vapor pressure of this ethane sample at 40° F. indicated good agreement with existing data (7) and a negligible change in vapor pressure with change in quality. An independent mass spectrographic examination confirmed that the level of impurities, primarily traces of nitrogen and argon, was below that stated by the vendor.

METHODS

The viscosity of helium near atmospheric pressure and the natural frequency of the stator and suspension were determined after each set of measurements for ethane at a particular temperature. Such procedures checked the consistency of the data. As shown in Figure 2, the trend in the elastic behavior of the suspension was the only measurable change in the behavior of the system with time.

Conventional high-vacuum techniques were employed to introduce the sample of ethane into the viscometer. The speed of rotation required to introduce a particular angular displacement in both directions of rotation was determined. This speed of rotation was established by a predetermined rate-drive (5) and was known within 0.02%. The speeds of rotation utilized to introduce the same angular displacement in the two directions were in agreement within 0.1%.

Measurements were first made at atmospheric pressure. The pressure was then raised to the highest value to be investigated at a particular temperature and was again reduced to atmospheric in an appropriate series of steps. This procedure made a comparison possible at each temperature of the measured values of the viscosity of ethane at atmospheric pressure before and after the measurements at the higher pressures. Upon completion of the program, check measurements were made to determine the viscosity at particular states where rapid changes in viscosity with environment were encountered. These check measurements permitted an evaluation of the stability of the rotating-cylinder viscometer with respect to time.

RESULTS

Results of this investigation are tabulated in micropoises because of the apparent widespread use of the units in engineering work. Experimental values are presented in Table I. The effect of pressure for each temperature investigated is portrayed in Figure 5 for pressures up to 1500 p.s.i.a. The more pronounced effect of pressure upon the viscosity of ethane at the lower temperatures is characteristic of the trend encountered with most hydrocarbons. Figure 6 presents the experimental data at pressures up to 5000 p.s.i.a. The curves shown in Figures 5 and 6 represent values which have been smoothed with respect to pressure and temperature.

Table II records smooth values of the viscosity of ethane for a series of pressures and temperatures. The standard error of estimate indicated in Table II assumes that all of the uncertainty lay in the measured values of viscosity and none in the associated measured pressures and temperatures. Information recorded in Table II has been presented to at least one more significant figure than is justified by the accuracy of the experimental measurements. Such a policy was followed to permit more accurate evaluation of the differences in viscosity with respect to changes in state. The smoothing operation is not believed to have introduced more than 0.001 fraction of uncertainty in the viscosity throughout the entire range of pressures and temperatures.

The residual viscosity, defined as the difference between the viscosity at attenuation and the viscosity at the pressure in question for the same temperature, is shown as a function of specific weight in Figure 7. Experimental points shown in Figure 7 yielded, from the single curve drawn through the data, a standard error of estimate of 0.008×10^{-6} pound second per square foot, or 38 micropoises, assuming that all the uncertainty lay in the experimental measurement of the viscosity and none in the specific weight. The rather close agreement of the experimental data with the single curve, even in the critical region, indicates the utility of this form of presentation.

Present data are compared with the recommended values of Eakin (8) and Baron (*1*) in Figure 8. Eakin and Baron appeared to obtain about 1.5% lower viscosity at atmospheric pressure than was obtained by the authors. Larger discrepancies, amounting to as much as 6% at a pressure of 1000 p.s.i.a. and a temperature of 125° F., were encountered in comparison with Baron's values. Except at

Table I. Experimental Measurements for Ethane

Pressure, P.S.I.A.	Viscosity, Micropoise
80° F.	
1295.5	515.03
1295.5	513.74
1294.4	505.60
1032.8	468.16
1034.7	464.95
1034.7	463.95
840.1	425.98
842.5	426.94
635.8	352.44
635.8	351.58
5194.8	833.62
5194.8	829.07
5188.3	828.02
4562.8	789.38
4562.8	790.91
4038.3	753.90
4036.4	753.71
3061.7	683.47
3062.0	685.05
2148.3	605.53
2147.3	605.48
2147.3	605.57
1546.5	545.44
1549.8	544.86
1048.9	473.81
1048.9	473.57
567.5	119.55
567.5	120.08
567.6	119.46
505.5	112.04
505.5	112.04
260.5	98.44
260.7	98.25
27.3	94.13
27.6	93.99
90° F.	
14.1	95.57
14.1	95.52
14.2	95.33
1272.4	468.97
1273.2	470.32
1273.2	470.17
1039.7	428.37
1040.6	428.61
889.0	390.21
889.4	390.93
757.0	337.64
758.6	337.40
596.6	123.19
596.6	122.86
596.6	123.34
497.3	112.08
497.3	112.75
497.3	112.23
253.3	100.26
253.3	101.50
253.3	100.31
705.1	183.42
705.1	184.53
705.1	183.33
599.8	126.98
600.7	126.78
601.2	126.54
100° F.	
5102.9	764.15
5090.0	762.52
5083.9	763.14
4029.0	712.39
4028.0	713.54
3034.1	624.53
3031.2	624.53
2027.7	534.19
2027.7	534.19
1011.5	378.72
1011.5	376.52
892.3	332.71
892.3	332.81
763.1	173.23
100° F. (*cont*).	
764.5	171.98
764.8	171.36
627.8	123.96
628.5	123.91
505.2	112.42
505.3	112.37
248.3	101.02
248.5	100.79
22.3	97.34
22.3	97.19
719.4	144.69
719.4	149.00
710.4	142.54
711.3	142.97
661.5	131.76
661.5	131.38
661.9	130.66
861.5	304.41
859.5	304.70
858.6	304.80
757.4	167.15
757.4	162.88
758.4	163.51
758.4	163.46
600.7	121.95
600.7	121.80
600.7	124.77
600.7	124.72
632.9	125.16
602.1	122.95
130° F.	
2110.4	455.38
2110.4	455.47
2081.4	453.56
2081.4	455.04
1253.5	316.10
1253.5	316.62
1278.3	314.76
1278.3	315.33
1102.2	251.51
1103.1	249.93
1103.1	250.12
1005.8	202.67
1005.8	201.91
1012.8	202.38
902.6	164.90
900.8	164.32
900.9	164.51
800.8	144.93
800.8	144.45
801.2	145.03
699.0	131.14
699.3	131.43
699.3	131.00
160° F.	
5109.9	624.25
5104.5	624.53
5099.7	625.30
3908.7	546.87
3908.9	546.73
2990.3	472.95
2987.6	473.24
2986.2	473.00
2050.6	376.81
2051.4	375.42
3443.5	511.35
3443.5	511.78
3443.5	511.20
3443.5	511.16
2585.1	435.17
2585.1	435.03
2585.8	434.84
2030.1	372.26
2030.6	371.21
2035.2	372.31
1527.4	285.74
1527.4	284.02
1527.4	283.49
1046.0	168.25
160° F. (*cont*).	
1046.0	167.34
1047.5	166.91
777.6	134.16
777.6	134.30
777.6	134.44
519.2	120.22
519.2	119.31
513.6	119.17
279.0	111.32
279.0	111.27
25.4	107.25
25.6	107.25
220° F.	
4646.1	489.99
4646.1	489.80
4649.8	490.47
3893.8	442.40
3897.9	443.22
3047.2	375.61
3048.7	374.84
2102.3	274.39
2102.8	273.61
1292.1	174.33
1293.4	172.60
646.4	129.85
646.4	130.04
33.8	116.97
33.8	116.59
280° F.	
3089.9	312.75
3089.3	311.74
3086.1	315.57
2228.9	240.35
2228.9	240.30
1535.0	184.00
1535.3	183.18
832.9	145.55
834.0	145.26
101.6	127.79
101.6	127.50
5225.9	452.17
5224.4	450.64
5224.4	450.35
4028.4	375.13
4028.4	389.11
4028.4	377.72
340° F.	
4840.7	377.62
4838.5	377.38
4055.8	333.57
4054.5	334.10
3013.9	267.64
3013.9	268.22
2038.0	208.75
2038.0	208.66
1037.1	157.71
1037.8	158.24
97.8	136.50
97.8	136.46
400° F.	
4973.5	349.66
4969.0	351.62
4969.0	348.37
4064.6	302.16
4061.5	304.46
4060.6	305.71
1032.6	165.18
1032.8	165.37
98.2	146.56
98.4	146.37
98.4	146.46
3052.2	253.14
3052.2	253.47
3052.2	254.67
2067.5	208.08
2067.5	209.18
2065.0	208.46

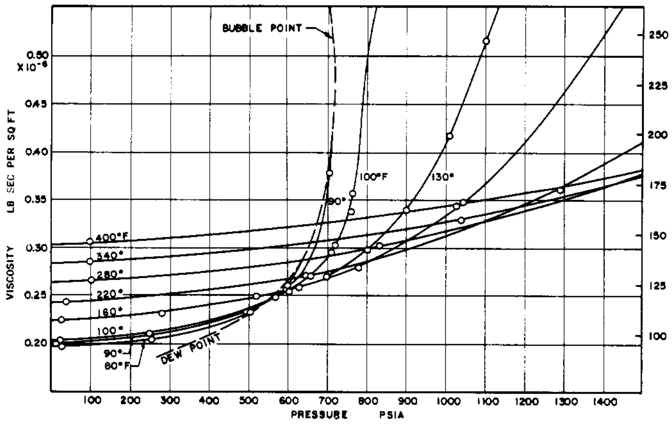

Figure 5. Viscosity of ethane at low pressures

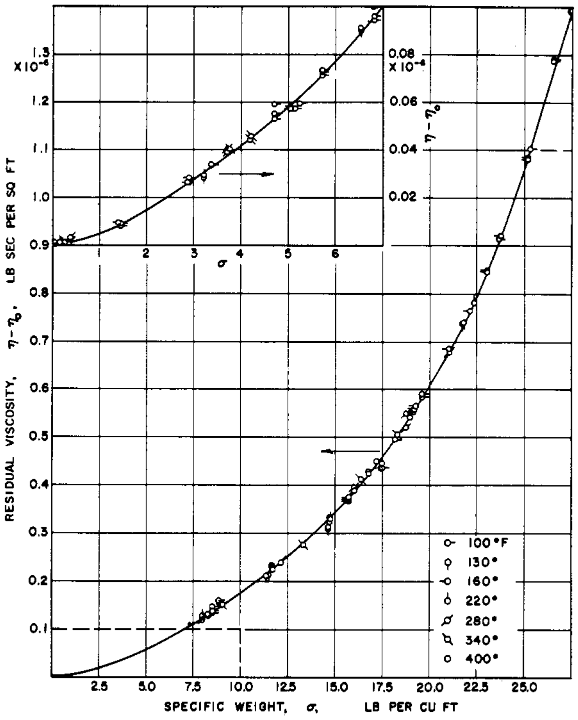

Figure 7. Residual viscosity as a function of specific weight

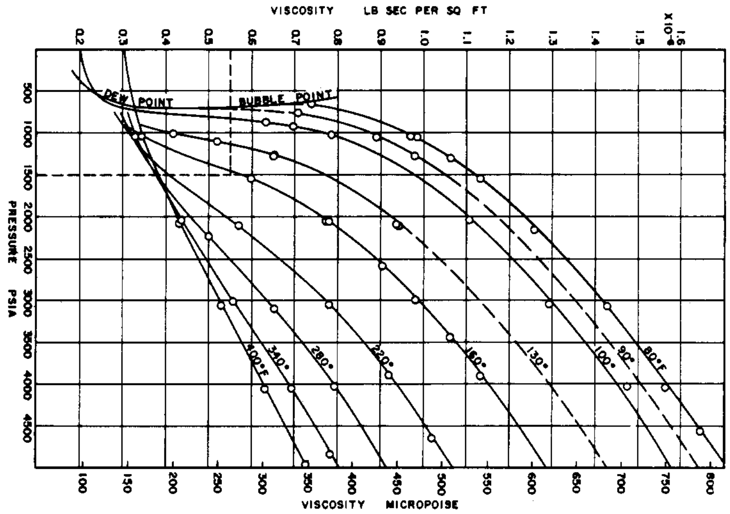

Figure 6. Viscosity of ethane at higher pressures

Table II. Viscosity of Ethane

Pressure, P.S.I.A.	Temperature, ° F.								
	80° F.	90° F.	100° F.	130° F.	160° F.	220° F.	280° F.	340° F.	400° F.
	(630.7)[a]	(715.5)							
Dew Point	136.22	216.65							
Bubble Point	331.32	226.23							
14.7	93.84[b]	95.52	97.05	...	106.91	116.49	125.78	135.40	144.88
200	96.95	98.63	100.07	...	109.36	118.64	128.12	137.51	146.65
400	104.62	105.96	107.25	...	115.15	123.05	131.91	141.00	149.77
600	126.40	124.49	122.33	...	122.57	128.03	136.12	144.59	154.17
800	414.63	356.79	250.41	143.35	136.45	136.93	143.16	150.24	158.96
1000	461.07	419.95	373.22	197.64	159.68	149.29	152.06	156.56	164.70
1500	538.64	503.21[c]	468.50	371.21	277.22	194.58	180.41	179.83	182.90
2000	592.50	561.14	531.46	444.22[c]	368.57	259.70	218.95	206.93	204.92
2500	638.85	608.06	579.62	497.46	427.32	321.27	262.66	237.10	227.81
3000	678.44	648.76	622.43	542:47	474.86	371.25	305.99	267.64	251.36
3500	715.69	687.06	661.35	582.69	516.09	413.15	344.44	299.05	275.93
4000	750.79	722.97	696.16	619.55	553.58	450.35	380.35	330.36	300.87
4500	785.93	755.05	727.09	654.98	587.09	481.85	409.84	359.09	325.67
5000	820.93	784.74	757.21	683.71	617.64	511.87	437.61	386.14	350.95
σ[d]	7.09	1.01	1.53	5.12	0.86	0.96	2.63	0.34	1.34

[a] Values in parentheses represent vapor pressure of ethane, p.s.i.a.
[b] Viscosity, micropoise.
[c] Values at this and greater pressures are extrapolated.
[d] Standard error of estimate, micropoise.

$$\sigma = [\{ \sum_{1}^{N} (\eta_e - \eta_s)^2 \}/N]^{1/2}$$

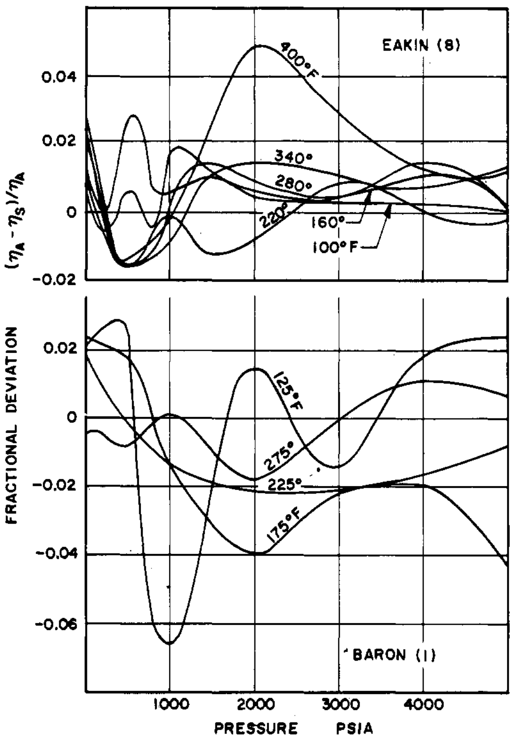

Figure 8. Comparison of present measurements with data of others (*1*) (*8*)

400° F. all of Eakin's recommended values fell within ±2.5% of the current measurements. It should be recognized that Eakin did not carry out measurements above 340° F. Agreement was better at the higher pressures than for pressures below 1000 p.s.i.a. The values of Eakin are predominantly smaller than those reported here, while those of Baron are somewhat larger.

ACKNOWLEDGMENT

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NOMENCLATURE

f = specific function
h = length of torsion cylinder, ft.
k = torsional elastic constant, ft. lb./radian
k_1 = configuration factor, 1/cu. ft.
k_2 = suspension factor, ft. lb./radian
N = number of experimental points
P = pressure, p.s.i.a.
r_1 = radius of torsion cylinder, ft.
r_2 = radius of rotating cylinder, ft.
S = speed of rotation, rev./sec.
t = temperature, ° F.
T = absolute temperature, ° R.
α = coefficient of thermal expansion, 1/° F.
ϵ_Y = Young's modulus, p.s.i.
η = viscosity, lb. sec./sq. ft. or poise
θ = time, sec.
λ = Poisson's ratio
σ = specific weight, lb./cu. ft.
σ' = standard error of estimate
ϕ = angular displacement, degrees or radian

Subscripts

A = authors
e = experimental
o = reference state
P = pressure
S = source
s = smooth
T = temperature
θ = time

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