THE REDWOOD VISCOMETER

By Winslow H. Herschel

ABSTRACT

The Redwood viscometer was selected for calibration because there appeared to be some doubt whether or not the instrumental constants varied with the temperature. By the use of oils whose viscosity had been determined in a capillary tube instrument the equation was obtained:

$$\text{kinematic viscosity} = 0.00260\, t - \frac{1.88}{t}$$

where t is the time of flow in seconds.

Two common errors in viscosimetry were investigated, with the following conclusions:

1. That the error due to inaccuracy in the Meissner formula for average head is negligible in ordinary work.

2. That the error due to cooling of the oil after leaving the outlet tube may be neglected at low temperatures but should be corrected at temperatures near the boiling point of water. Thus, any observed variation in instrumental constants at different temperatures is probably due to the last-mentioned error, so that viscosimeters may be calibrated at any convenient temperature, and outlet tubes may be made of any suitably durable and noncorrosive material without regard to its coefficient of expansion.

CONTENTS

1. INTRODUCTION

It is generally believed necessary to standardize viscosimeters or viscometers at more than one temperature. If this is correct, all instruments of a given type must be made of material of approximately the same thermal coefficient of expansion, and the use of only one calibrating liquid at two different temperatures would be inadequate, even if the experimental error were assumed negligible.

Waidner [1] found conversion factors between the Saybolt Universal, Engler, and Redwood instruments by flow tests made at 70 to 210° F (21.1 to 98.9° C) and concludes:

The fact that these factors (for the Saybolt Universal and Engler viscosimeters) show no systematic variation with temperature therefore indicates that if the oil in

[1] C. W. Waidner, Proc. A. S. T. M., 15, part 1, p. 286; 1915.

the jet is not at the same temperature as the oil in the main portion of the viscosimeter any effect due to this cause is the same for the two types of instruments. The conversion factors found for the Redwood viscosimeter seemed, on the other hand, to depend not only upon the efflux times but to some extent upon the temperature.

In previous work by the author[2] the range of temperatures was insufficient to throw any light on this subject, and it therefore seemed desirable to determine whether or not conversion factors depended solely upon the kinematic viscosity or upon kinematic viscosity and temperature.

2. DESCRIPTION OF REDWOOD VISCOMETER

The Redwood viscometer,[3] which is standard in England, is of the same general efflux type as the Engler, of Germany, and the Saybolt Universal, which has been adopted as standard for lubricating oils in the United States.[4] The Redwood differs from these other instruments in being provided with an agate outlet tube, a feature which Redwood, in designing his instrument in 1885, copied from an earlier instrument of Charles Rumble.[5]

The instrument consists of a silvered brass container about 1⅞ inches in diameter by about 3½ inches in depth (4.76 by 8.89 cm). A 1-inch (2.54 cm) tube, closed at the lower end, projecting at an angle of 45 degrees from the side of the bath near the bottom, provides a means of heating the bath without danger of overheating the agate. The bath is also furnished with a drain cock.

The flow of oil is controlled by a small brass sphere attached to a wire, the sphere resting in a hemispherical cavity in the agate. This is open to the same objection as the skewer used with the Engler instrument, that it might cause wear of the outlet tube. It is also apt to leak, so that the flask can not be placed under the instrument until immediately before starting the flow.

In the Redwood instrument, as in the Engler, the thermometer is left in the oil during the test. As the bulb is completely submerged at the end, there is no question in regard to accuracy of reading, as with the Engler, where the bulb is partly exposed. The thermometer stem must be of standard diameter, but the dimensions of the bulb have no influence upon the average head.

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[2] B. S. Tech. Papers, Nos. 100, 112, and 125.

[3] For illustrations of this instrument see Holde-Mueller, Examination of hydrocarbon oils, p. 114, 1915; L. Archbutt and R. M. Deeley, Lubrication and lubricants, p. 167, 1912; B. Redwood, A treatise on petroleum, 2, p. 276, 1913.

[4] A. S. T. M., Standards adopted in 1920, p. 104; Bulletin No. 5, Committee on Standardization of Petroleum Specifications, p. 28, issued by the Bureau of Mines, 1921; Tests and testing standards adopted by the National Petroleum Association, Sept. 22, 1920.

[5] B. Redwood, Jour. Soc. Chem. Ind., 5, p. 124–5; 1886.

The height of filling is determined by a single gage point instead of the three points of the Engler and the overflow rim of the Saybolt. The instrument is provided with leveling screws.[6]

3. DIMENSIONS

The essential dimensions of the Redwood viscometer are given in Table 1, according to different experimenters.

TABLE 1.—Dimensions of Redwood Viscometer

Name of dimension	Higgins [a]		Meissner [b] No. 1263	Bureau of Standards	
	Normal	Tolerance		No. 1004	No. 1025
	cm	cm±	cm	cm	cm
Diameter of outlet tube d	0.15	0.003	0.158	[c] 0.1654	0.1583
Length of outlet tube, l	1.00	.01	1.023	.9853	.9639
Height of gage point above bottom of outlet tube, h_1	9.25	[d] .64	9.615	8.861	9.400
Diameter of container, D	4.68	.02	4.658	4.589	4.695
Average head (calculated) h	[e] 7.67		8.059	7.211	7.838
Diameter of stem of oil-cup thermometer	.63				
Diameter of bulb of oil-cup thermometer	.80				
External diameter of agate, upper end [f]	1.27	.10			
External diameter of agate, lower end [f]	1.15	.10			
Height of base of container [g]	.80	.05	.852		

[a] W. F. Higgins, Collected researches, National Physical Laboratory, 11, p. 5; 1914.

[b] W. Meissner, Chem. revue über die fett und harz industrie, 19, p. 9; 1912.

[c] This is considerably above the normal dimension reported by Higgins, but Archbutt and Deeley, p. 166, give d as "very nearly" 0.17 cm, with l=1.2 cm.

[d] Higgins gives the initial head in two parts, the height of gage point above the upper end of outlet tube being 8.25±0.63.

[e] Not given by Higgins.

[f] The importance of these dimensions appears to be mainly in shop construction.

[g] This is the height of junction of cylindrical portion of oil cup with concave bottom of cup above upper end of outlet tube.

The last dimension of Table 1 appears to be needlessly restricted. As 50 cc of oil are run out in a test, the oil level falls 2.96 cm, so that this dimension could have a maximum value of 5.29 cm (instead of 0.85), and the oil surface at the end of run would still be within the cylindrical part of the container, which is a necessary condition in order that the average head may be correct.

The bulb of the thermometer must be placed somewhere within the above-mentioned 2.96 cm, so as not to be exposed at the end of run and so as not to be too near the outlet tube and thus obstruct the flow. It seems probable that more reproducible results could be obtained if the exact location were specified.

There is some uncertainty about the standard dimensions, because Higgins says he expressed them in millimeters for conven-

[6] For a consideration of the error due to inaccuracy in leveling see W. F. Higgins, Collected researches, National Physical Laboratory, 11, p. 6; 1914.

ience in comparing the Redwood and Engler instruments. This might be taken to imply that the real standardization is in inches. The diameter of the thermometer stem, for example, is obviously the equivalent of 0.25 inch, but the equivalent in inches of the inside diameter of the outlet tube is not so obvious, and it may be standardized in the metric system or have no other standardization than that of flow tests.

As has been noted in previous papers the Meissner formula for average head is not exact, because the kinetic energy correction was neglected in its derivation. The author is indebted to Dr. H. L. Dryden of this Bureau for an accurate equation for determining the average head when the kinetic energy correction is not neglected.[7]

For most purposes it is accurate enough to use Meissner's formula

$$h = \frac{h_1 - h_2}{\log e\left(\frac{h_1}{h_2}\right)} \qquad (2)$$

as has been done throughout this paper. If the accuracy of the experimental work or the large value of $h_1 - h_2$ justifies it, equation (2) may be used to get a preliminary value of the kinematic viscosity and to calculate C (see footnote 7), using the approximate values of $L = l + 0.25\ d$ and $m =$ unity, or more accurate values if known.

For the Saybolt Universal viscosimeter of normal dimensions the average head is 7.36 cm by equation (2) and 7.54 by equation (1), with t having a minimum value of 32 seconds. The maximum possible error due to using Meissner's formula is thus 2.4 per cent. With the Redwood instrument, assuming a kinematic viscosity of 0.025, the average head is 5.67 cm by equation (1) and 5.63 by equation (2), the difference of 0.7 per cent being negligible in the present work, since, as it should be remembered, this is the maximum error and decreases as the viscosity increases.

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[7] Dryden's equation is as follows:

$$1 - \sqrt{1 + Ch} = \frac{\frac{1}{2}(y_2^2 - y_1^2) + y_1 - y_2}{y_2 - y_1 + \log e\left(\frac{y_1}{y_2}\right)} \qquad (1)$$

where $y_1 = 1 - \sqrt{1 + Ch_1}$

$y_2 = 1 - \sqrt{1 + Ch_2}$ (where h_2 = Final head at end of run),

m = coefficient of kinetic energy correction,

$C = \frac{g\ d^4\ m}{256\ (k.\ v.)^2\ L^2}$ $k.\ v.$ = kinematic viscosity,

$= \frac{\text{absolutely viscosity in poises}}{\text{density in grams per cc}}$,

L = effective length of outlet tube = measured length + Couette correction,

g = acceleration of gravity = 981 cm per sec.^{2}

4. THE COOLING ERROR

It has long been known that there is an error with most commercial viscosimeters due to the cooling of the oil after it leaves the outlet tube, the effect being the same as if the flask were too large. To obviate this difficulty with the Engler viscosimeter, Engler and Kunkler [8] designed an instrument in which the flask is inclosed in a double-walled air bath. With the Barbey ixometer, with which the recorded "fluidity" is the volume discharged in cubic centimeters per hour, when the test is run for 10 minutes under a constant head, the volume is not read until the flask has been reheated to the nominal temperature of test.

In the directions for the Redwood viscometer Archbutt and Deeley say:

> If the test is to be made at a temperature more than a few degrees above or below that of the air of the room, the flask must be immersed in a bath of liquid heated to the testing temperature, or the body of the flask may be surrounded by a thick layer of cotton wool contained in a beaker, the neck and graduation mark being left exposed to view.

It is obvious that any conversion table would be inaccurate if used for comparison between readings of a Redwood viscometer when the above direction was obeyed and a Saybolt Universal instrument for which no such direction has been given. It will be assumed that the true conversion table which is desired is accurate when both instruments have been corrected for the cooling error, either by keeping the flask warm or by applying a correction to the observed time when necessary.

Fig. 1, which was calculated from Table 2, may be used to estimate the cooling error. Table 2 is in accord with former publications of the Bureau of Standards,[9] but gives the information in more convenient form for use in viscosimetry.

The density at 60° F (15.6° C) in grams per cubic centimeter may be taken as 0.001 less than the specific gravity as given in Table 2.

Fig. 2 is also needed to find the cooling error and has been calculated for the Saybolt Universal and Engler viscosimeters as well as the Redwood. If there is any appreciable error in the flask itself, the net or combined error must be used in entering Fig. 2 in order to get the combined error due to incorrect volume of flask and to cooling. The lines marked "max." and "min." show errors in time of flow due to the departure of the dimensions from

[8] L. Archbutt and R. M. Deeley, Lubrication and lubricants, pp. 168, 175, 1912; B. Redwood, A treatise on petroleum, 2, p. 280, 1913.

[9] H. W. Bearce and E. L. Peffer, B. S. Tech. Papers, No. 77, 1916; B. S. Circular No. 57, 1916.

the normal or mean values while still being "standard" or within the permissible variations. The dotted line for the Redwood viscometer was calculated from experimental data of Higgins, while the other lines are based solely upon calculated variations in average head due to variations in volume discharged.

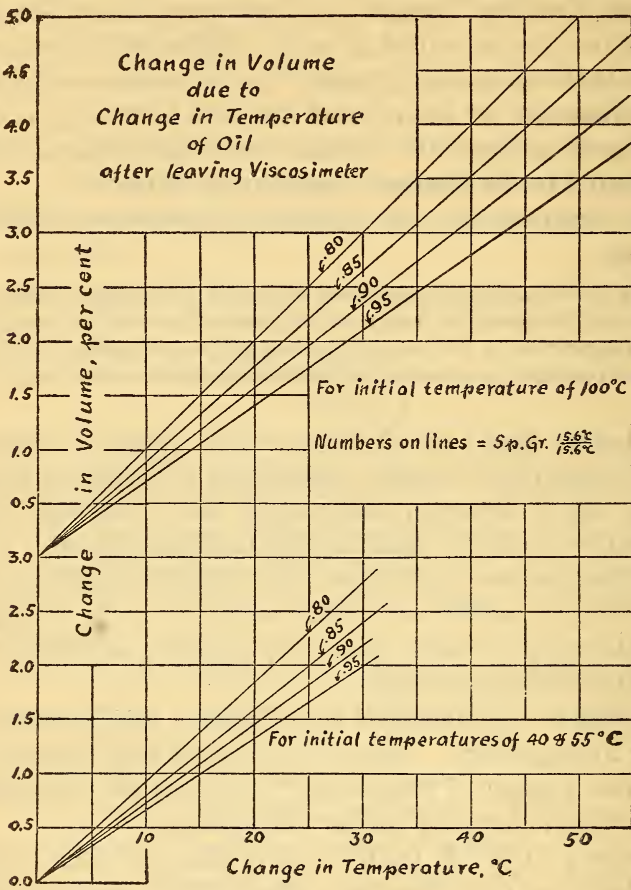

FIG. 1.—*Diagram showing change in volume of oil after leaving outlet tube*

Considering only instruments of normal dimensions, it will be seen that the error in time of flow is slightly greater than the error in volume for the Redwood and Engler instruments and about twice as great as the error in volume with the Saybolt Universal. The cooling error can not be considered negligible when tests are made at 210° F (98.9° C), and it seems probable that differences in conversion factors at different temperatures which might be observed could be ascribed to differences in cooling error, rather than to a difference in the thermal coefficient of expansion of the outlet tubes.

TABLE 2.—Change in Density of Petroleum Oils with Change in Temperature

Specific gravity $\frac{15.6°}{15.6°}$ C	Change in density per degree—		Specific gravity $\frac{15.6°}{15.6°}$ C	Change in density per degree—	
	C	F		C	F
0.630	0.00098	0.000544	0.798	0.00073	0.000406
.640	.00096	.000534	.808	.00072	.000400
.650	.00094	.000522	.817	.00071	.000395
.659	.00093	.000517	.827	.00070	.000389
.669	.00092	.000511	.837	.00069	.000383
.679	.00090	.000500	.847	.00068	.000378
.689	.00089	.000495	.857	.00068	.000378
.699	.00088	.000489	.867	.00067	.000372
.709	.00087	.000484	.877	.00067	.000372
.719	.00085	.000472	.887	.00067	.000372
.729	.00084	.000467	.897	.00066	.000367
.739	.00083	.000461	.907	.00066	.000367
.748	.00081	.000450	.917	.00066	.000367
.758	.00080	.000445	.927	.00066	.000367
.768	.00078	.000433	.937	.00066	.000367
.778	.00076	.000422	.947	.00066	.000367
.788	.00075	.000417	.957	.00066	.000367

The difference in temperature between the nominal temperature of test and the temperature of flask at end of run would naturally depend upon the room temperature, the viscosity of the oil, and the temperature of test. Fig. 3 shows that the cooling of the flask, and hence the cooling error, is negligible at low temperatures. The data are insufficient to indicate the extent to which the amount of cooling will vary with the room temperature or with the temperature of the oil bath for a given nominal temperature of test.

The American Society for Testing Materials [10] puts the responsibility for selecting the proper bath temperature upon the operator and merely says:

> The bath shall be held constant within 0.25° F (0.14° C) at such a temperature as will maintain the desired temperature in the standard oil tube.

It is commonly supposed that for the Saybolt Universal viscosimeter the bath should be kept at 100.25, 130.5, and 212.0° F (37.9, 54.7, and 100° C), respectively, for the three standard temperatures, but tests at the Bureau of Standards seem to indicate that

[10] Standards adopted in 1920, p. 105.

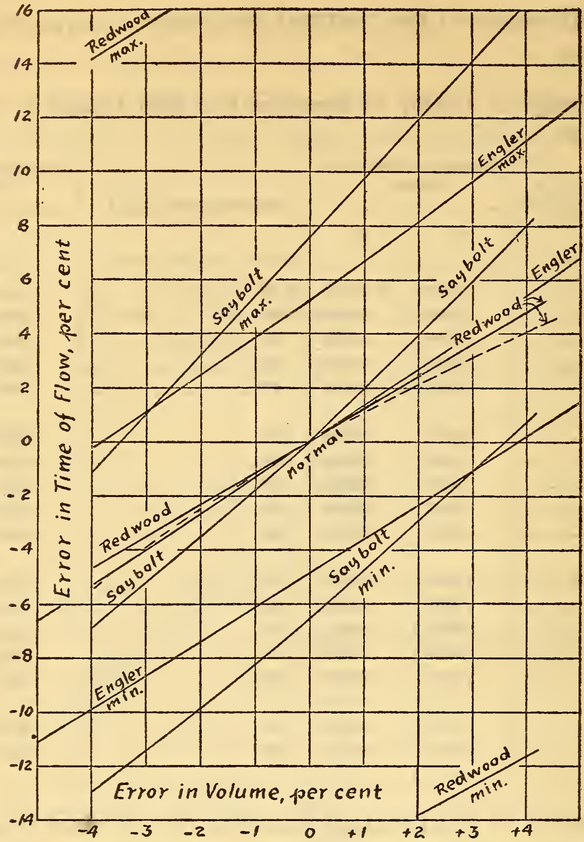

FIG. 2.—*Diagram for determining cooling error*

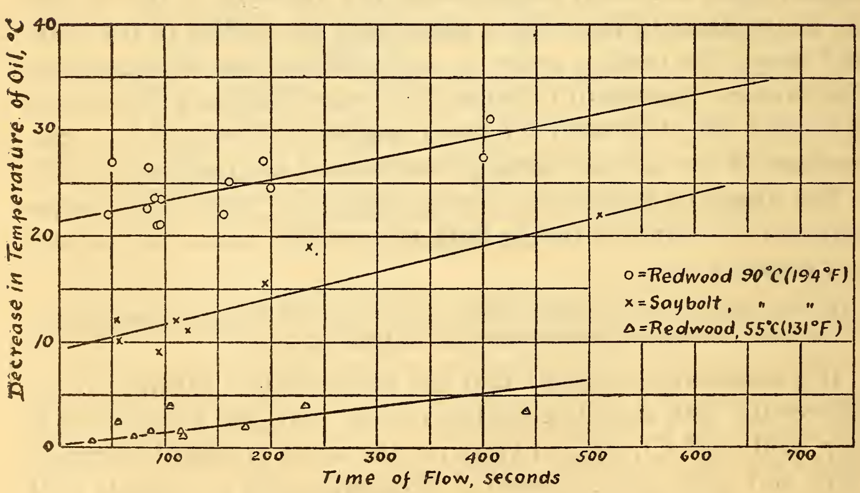

FIG. 3.—*Diagram showing decrease in temperature of oil in flask*

these temperatures are too low. The work was planned at a time when a committee of the American Society for Testing Materials [11] had proposed as standard temperatures, 20, 40, 55, and 100° C (68, 104, 131, and 212° F), and the proper excess of bath temperature over the nominal temperature of test was found to be as shown in Table 3.

TABLE 3.—Excess of Bath Over Test Temperature

Saybolt viscosity in seconds	Temperature of test—					
	104° F=40° C		131° F=55° C		212° F=100° C	
	° C	° F	° C	° F	° C	° F
32	0.7	1.3	0.8	1.4	1.3	2.3
60	.7	1.3	.8	1.4	1.3	2.3
90	.9	1.6	.9	1.6	1.4	2.5
120	.9	1.6	.9	1.6	1.4	2.5
150	1.0	1.8	1.0	1.8	1.6	2.9
180	1.0	1.8	1.1	2.0	1.8	3.2

If a steam bath at 212° F does not keep the oil under test at a temperature of 210° F, this standard temperature has no value whatsoever, and it is objectionable in any case, because there is always danger that the variations of steam temperature with the barometer will be overlooked.

The subject of bath temperature is more important with the Saybolt than with the Redwood or Engler instruments, because with the two latter the thermometer is kept in the oil during the run. A viscosimeter of the Saybolt type which is provided with a cover to support the thermometer in the oil during the test, is in use at the Bureau of Standards and gives the same time of flow as the usual Saybolt instruments. The instrument is provided with interchangeable tips of monel metal of the standard dimensions for the Saybolt Universal and Saybolt Furol viscosimeters.

5. STANDARDIZATION

In cases where a calibrating liquid of greater viscosity than water is required it is common to make use of sucrose or glycerin solutions, although they are both objectionable at high concentrations. With the former the viscosity changes very rapidly with the concentration, while the density which is used to determine

[11] Proc. A. S. T. M., 17, part 1, p. 463, 1917; 18, part 1, p. 321, 1918.

the concentration changes very slightly. Glycerin is objectionable because it is hygroscopic and because, according to Bawtree [12]—

Glycerin is not to be depended upon as a standard of viscosity. It possesses some internal structure which is broken down by repeatedly passing the same sample through the instrument till a minimum viscosity is reached. Physicists who have relied upon glycerin for standardizing their various viscometers have questioned this result, but glycerin manufacturers state that this state of stress in the material is an ordinary factor with which they have to deal and that the Hadfield-Bawtree viscometer results bear out their own experience.

Rape seed or colza oil is commonly used in Europe as a lubricant, and it is used to some extent in this country for compounding. Its viscosity approaches the average of that for petroleum lubricating oils. It is therefore used as a calibrating liquid for the Barbey ixometer and the Martens[13] oil-friction testing machine, as well as for the Redwood viscometer.

Redwood was aware that a calibration by means of flow tests with a single liquid at a single temperature was inadequate and must be supplimented by standard dimensions. Speaking of glass pipettes, he says:

It is a serious objection to the pipette that the results afforded vary to some extent with the shape of the constricted portion of the tube. Two pipettes may be constructed with jets of such size that they deliver equal quantities of a given oil at a given temperature in a given time; but if the jets vary materially in form the two instruments will not furnish concordant results with oils of greater or less viscosity than that of the oil with which they were standardized.

This applies, though to a less extent, to all efflux viscosimeters, even when of standard dimensions, because it is always necessary from practical considerations to allow a certain variation or tolerance on all dimensions. Redwood makes his final adjustments by varying the hydrostatic head, and says:

The necessary amount of correction is so small that I have not, in practice, found that any objection attaches to the method adopted.

It will be noted that, according to the equation for viscous flow, if two instruments are to agree at all viscosities it is necessary only that the lengths of outlet tube shall be equal, and that there shall be equal values of d^4h. The first requirement is met by the standard dimensions and the second by adjusting the head. According to Higgins—

The diameter of the jet in the Redwood viscometer is not rigidly fixed by measurement, but it is to be of such a size that 50 cc of rape oil will have a time of flow at 60° F. (15.6° C.), equal to 535 seconds, when the filling mark is adjusted to within 6.3 mm of its normal position. This corresponds approximately to a permissible variation of ± 2 per cent in the diameter of the jet.

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[12] A. E. Bawtree, Jour. Oil and Color Chemists Assn., 3, p. 109, 1920.

[13] Holde-Mueller, Examination of hydrocarbon oils, p. 124, 1915.

In reality the values of 535 seconds for the time of flow and 0.915 as assumed for the density are purely arbitrary, as shown by Table 4 from tests of 10 samples by Crossley and Le Sueur.[14]

TABLE 4.—Density and Viscosity of Rape-Seed Oil, According to Crossley and Le Sueur

Specific gravity at 60° F=15.6° C	Time of flow in seconds, Redwood viscometer, at 70° F=21.1° C
0.9141 (minimum)	413.8
.9165	369.4 (minimum)
.9171	464.6 (maximum)
.9177 (maximum)	371.0

The variation in viscosity is therefore about 20 per cent, as compared with 2.5 per cent for castor oil.[15] Archbutt[16] found a variation of 27 per cent for 22 samples of rape-seed oil. In short, there seems to be no value to rape-seed oil as a calibrating liquid except the psychological value of a tradition, and a mineral oil would serve the purpose much better because changing less in viscosity with time.

It is a question whether in the manufacture of the Saybolt Universal viscosimeter a certain barrel of oil or a certain instrument is taken as the ultimate standard, to which the standard dimensions secure merely an approximation. With the instruments as hitherto constructed, it has been found that a burr forms at the upper end of the outlet tube and causes an increase in the time of flow. This burr is apparently caused by the rubbing of the thermometer bulb across the upper end of the outlet tube.

Redwood says concerning his instrument:

> The author attaches considerable importance to the employment of agate in the construction of the jet, as this material is not liable to become worn or injured, even if the instrument is subjected to somewhat rough usage. He has had one of these viscometers in almost daily use in his laboratory at temperatures ranging from 70 to 250° F (21.1 to 121.1° C) for the past 25 years, and the jet shows no sign of wear.

If this means there is no change in the time of flow for a definite chemical compound, it is a remarkable record. Neither oil nor instrument is satisfactory as an ultimate standard, since the viscosity of a sample may change with time, and any instrument is liable to injury or destruction by fire or otherwise. If a certain sample of oil is the standard, then it is necessary periodically when the sample becomes exhausted to select a new sample, with danger

[14] Quoted by J. Lewkowitsch, Chemical technology and analyses of oils, fats, and waxes, 2, p. 199, 1909.
[15] Winslow H. Herschel, B. S. Tech. Papers, No. 112, p. 24, 1919.
[16] L. Archbutt, Jour. Soc. Chem. Ind., 5, pp. 132, 310, 1886.

of a gradual accumulation of errors. The only satisfactory ultimate standard must be based on numerical values, as, for example, an equation of the form

$$\text{kinematic viscosity} = k.\ v. = At - \frac{B}{t}, \qquad (3)$$

as tentatively adopted by the National Petroleum Association[17] for the Saybolt Universal, Engler, and Redwood instruments.

6. RESULTS OF TESTS

As the Bingham viscometer, which was used in determining the viscosities of calibrating liquids, can not conveniently be run at

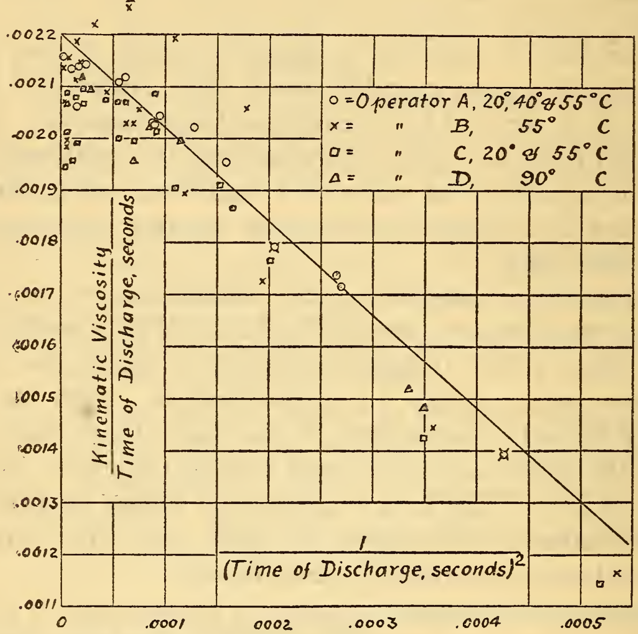

FIG. 4.—*Higgins diagram for Saybolt Universal viscosimeter No. 109*

100° C (212° F) the somewhat lower temperature of 90° C (194° F) was selected in addition to the temperatures of 20, 40 and 55° C previously mentioned in connection with Table 3. The methods of determining instrumental constants from the results of flow tests have been fully described in previous papers.

Figs. 4 and 5 show Higgins and Herschel diagrams for Saybolt Universal viscosimeter No. 109. In Fig. 4 the graph is drawn from equation (3), with $A = 0.00220$ and $B = 1.80$ as determined in previous work. It seems possible that the points indicate a

[17] Tests and testing standards recommended by the department of standards and tests, N. P. A., Sept. 22, 1920. See also Proc. A. S. T. M., **21**, p. 362; 1921.

lowering of the graph or a decrease in the constant A, due to the burr previously referred to. This was to be expected, since it was found after these tests were finished that a perceptible burr had formed at the top of the outlet tube, which had to be removed to restore the instrument to standard dimensions. No systematic variation of A with the temperature can be observed.

In Fig. 5 the calibration graph was drawn as calculated from the dimensions of instrument No. 109 and with the Couette and kinetic energy corrections also taken from Bureau of Standards Technologic Paper No. 112. The decrease in the value of A is here indicated by the location of most of the points to the right of the graph. Tests of operator B are apparently less exact, and tests at very high viscosities—say, with values of Reynold's criterion below 10—should be disregarded on account of error in the assumed viscosities of the calibrating liquids.[18]

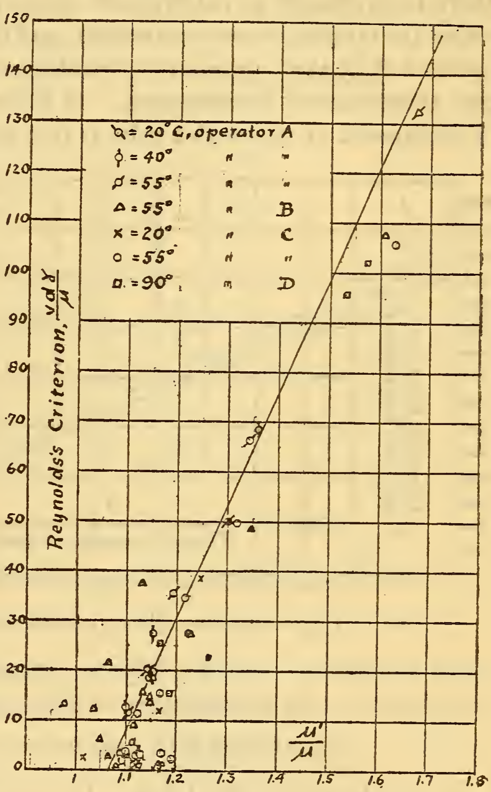

FIG. 5.—*Herschel diagram for Saybolt Universal viscosimeter No. 109*

Fig. 6 shows a Higgins diagram for the Redwood instrument. The change in slope near the bottom of the graph indicates the critical velocity, which is the highest velocity for which the instrument should be used. The time of flow is here 30.4 seconds, while Reynold's criterion is 700, as compared with 800 for the Saybolt Universal viscosimeter at the critical velocity. The dotted line, which represents fairly well the results of Archbutt and Deeley, was calculated from a diagram giving results of tests by the Texas Co. on instrument No. 1326.[19]

[18] The source of error will be discussed in another paper. It will be sufficient to point out here that the error is indicated at high viscosities by the points being too low on a Higgins diagram (Fig. 4) or too far to the right on a Herschel diagram (Fig. 5).

[19] Lubrication, 7, p. 5, May, 1921.

Figs. 7 and 8 show Herschel diagrams for Redwood viscometers Nos. 1004 and 1205. As in Fig. 5 there is no indication of any effect of a change in temperature. The points obtained at 90° C (194° F) were corrected for cooling error, the maximum correction in time of flow being 2.8 per cent, or slightly less than the maximum of 3.4 per cent for the Saybolt Universal, Figs. 4 and 5. The error was negligible at lower temperatures.

It is believed that this proves that within the experimental error there is no change in calibration due to change in temperature provided the cooling error is corrected, and that the commonly accepted opinion that it is necessary to calibrate viscosimeters at more than one temperature is erroneous. It shows, also, that the coefficient of expansion of the outlet tube is not important, and that the ma-

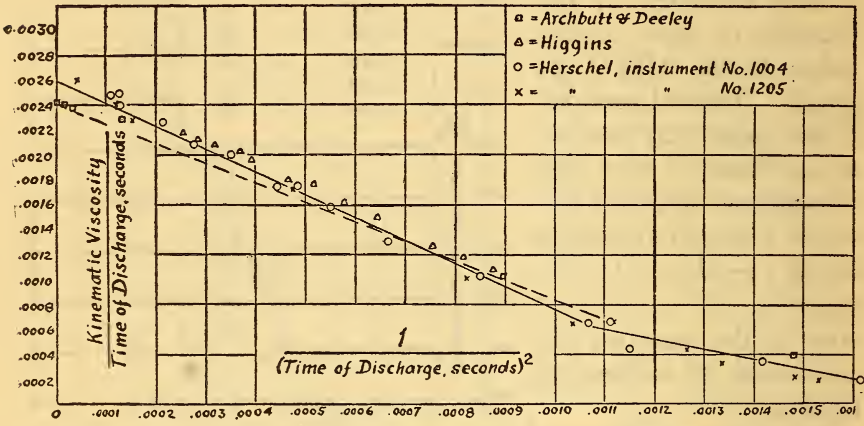

FIG 6.—*Higgins diagram showing critical velocity for Redwood viscometer*

terial should be chosen solely on grounds of ease and accuracy of manufacture and permanency of dimensions when once completed.

7. EQUATION FOR THE REDWOOD VISCOMETER

It may be seen from Table 1 that instrument No. 1025 is not of standard dimensions, the outlet tube being too short. Fig. 8 indicates that the Couette correction has a negative value, which is unusual, and the author has previously expressed the opinion that it is always positive.[20] Knibbs,[21] who takes the correction as $\frac{nd}{2}$, found that n was sometimes positive and sometimes negative, and says:

> No general value, unless it be zero, can be assigned to n. Hence, no correction should be applied to the length of a tube unless experiments therewith clearly indicate its propriety.

[20] Trans. A. S. C. E., 84, p. 527; 1921.

[21] G. H. Knibbs, Jour. and Proc. R. S., New South Wales, 29, p. 105, 1895.

For these reasons the tests on instrument No. 1025 have been disregarded and the Redwood equation based entirely on tests with instrument No 1004.

From Fig. 7 and the dimensions of Table 1 the Couette correction = 0.01 cm = 0.06 *d*. That this is much less than found for the Saybolt Universal viscosimeter may be due to the fact that the piece of agate in the Redwood instrument is concave at the top and convex at the bottom, which probably reduces the effect of

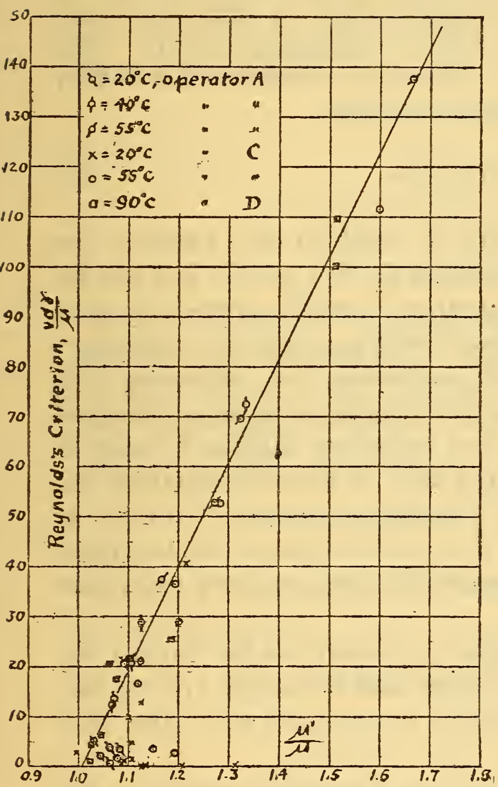

FIG. 7.—*Herschel diagram for Redwood viscometer No. 1004*

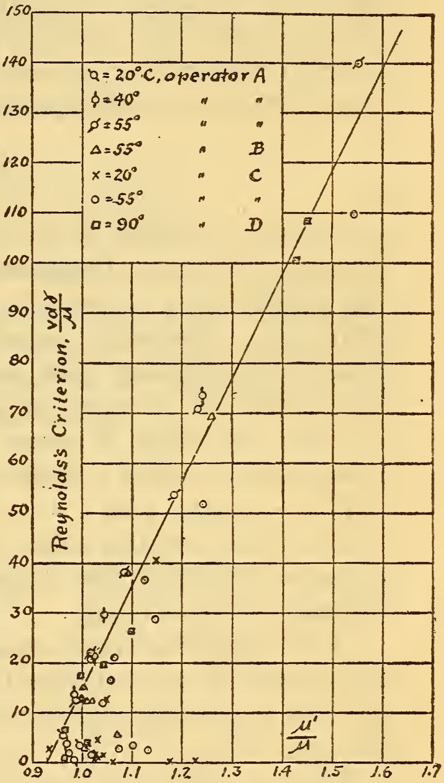

FIG. 8.—*Herschel diagram for Redwood viscometer No. 1025*

surface tension. Fig. 7 also gives the value of 0.953 for the coefficient *m* of the kinetic energy correction.

In equation (3)

$$A = \frac{\pi\, g\, d^4\, h}{128\, Q\, L}, \tag{4}$$

where Q is the volume of oil run out in the measured time, or 50 cc, for the Redwood instrument. The second instrumental constant may be found by the equation

$$B = \frac{Q\ m}{8\ \pi\ L}. \tag{5}$$

From equations (3) to (5), the dimensions of the instrument, and the above values of m and the Couette correction, the equation for Redwood instrument No. 1004 may be obtained as

$$k.\ v. = 0.00259\ t - \frac{1.905}{t}. \tag{6}$$

There is considerable difficulty in correcting equation (6) so that it will apply to an instrument of normal dimensions, since the Redwood viscometer is partly standardized by dimensions and partly by the time of flow of a liquid of unknown vicosity. The attempt will however be made. Since the velocity of flow is very small for rape-seed oil, equation (3) becomes

$$t = 535 = \frac{k.\ v.}{A}, \tag{7}$$

and since, according to the data of Archbutt and Deeley,[22] the kinematic viscosity of rape-seed oil at 60° F (15.6° C) is 1.223 for one sample and 1.285 poise for another, A would approach 0.00229 or 0.00241. The lack of agreement with equation (6) emphasizes what has previously been said concerning the vagueness of a standardization by means of such a variable material as rape-seed oil. On the whole, it seems best to accept Higgins's value of 0.00260 for A, which is almost the same as found in equation (6).

If $A = 0.00260$ and $L = 1.01$, equation (4) gives $d = 0.163$. It will be noted that this value of d, as well as those in the last three columns of Table 1, are all greater than the supposed maximum allowable value of 0.153.

If B is calculated from equation (5) exactly as the value 1.905 of equation (6) was calculated, except that the length l of the outlet tube is given its normal value of 1.00 cm, the new value of B becomes 1.877.

Higgins's value of B was 1.715, but it seems impossible to get this value on any assumption in accordance with the tests. If the Couette correction were negative, as indicated by tests on instrument No. 1205, then A as well as B would be increased, and both constants would be in poorer agreement with other experimenters. There is no evidence that the value of m should be decreased, as it is already less than the theoretical value of 1.12 or the value 0.989 previously found for the Saybolt Universal viscosimeter. If it is assumed that Higgins's instrument had the maximum allowable length of outlet tube, 1.01 cm and $L = 1.02$, it

[22] L. Archbutt and R. M. Deeley, Lubrication and lubricants, p. 190, 1912.

would follow from equation (5) that $B=1.859$. To still further reduce the value of B it might be assumed that the Couette correction $=0.466\ d$, as with the Saybolt, and that $d=0.15+2$ per cent $=0.153$ cm. This would give a value of $L=1.08$ cm and $B=1.755$, which is still higher than Higgins's value.

On the whole, the evidence appears to be that Higgins's values of $d=0.15$ cm and $B=1.715$ are both too low for an instrument of normal dimensions. The most probable value of B is 1.88, so that the complete equation for a Redwood viscometer of normal dimensions would be

$$k.\ v. = 0.00260\ t - \frac{1.88}{t}, \tag{8}$$

from which

$$t = 192.3\ k.\ v. \left(1 + \sqrt{1 + \frac{0.01952}{(k.\ v.)^2}}\right). \tag{9}$$

8. CONVERSION TABLES

In previous work[23] Higgins's equation was used tentatively as probably the best available, but this may now be replaced by equations (8) and (9). Similar equations for the Saybolt Universal and Engler instruments are as follows:

For the Saybolt Universal—

$$k.\ v. = 0.00220\ t - \frac{1.80}{t} \tag{10}$$

$$t = 227.3\ k.\ v. \left(1 + \sqrt{1 + \frac{0.01584}{(k.\ v.)^2}}\right), \tag{11}$$

and for the Engler—

$$k.\ v. = 0.00147\ t - \frac{3.74}{t} \tag{12}$$

$$t = 340.3\ k.\ v. \left(1 + \sqrt{1 + \frac{0.02196}{(k.\ v.)^2}}\right). \tag{13}$$

Equations (12) and (13) were derived for instrument No. 2204U with a water rate of 51.3 seconds, but they are the best available for an Engler instrument of normal dimensions.

Equations (8) to (13) have been used to calculate Tables 5 to 8, giving multiplying factors to convert readings of one instrument into those of either of the other two or into kinematic viscosity, which serves as an international language. Each table begins with the lowest viscosity for which the instrument mentioned in the first column should be used. The multiplying factors given in the last line hold good for all higher viscosities.

[23] Winslow H. Herschel, B. S. Tech. Papers, No. 112, p. 22, 1919.

9. CONCLUSION

1. There is no change in instrumental constants due to change of temperature of test, so that instruments may be calibrated at any convenient temperature, varying the viscosity either by change of temperature or by blending.

2. The error due to inaccuracy of the Meissner formula for average head is not serious.

3. The error due to change in volume of the oil after it leaves the outlet tube is not a major error in viscosimetry and is negligible at all usual temperatures of test except 210 or 212° F (98.9 or 100° C).

4. The most probable equation for the Redwood No. 1 or standard Redwood viscometer is

$$\text{kinematic viscosity} = 0.00260\,t - \frac{1.88}{t},$$

necessitating a slight change in the tentative tables given in Bureau of Standards Technologic Paper No. 112.

TABLE 5.—Viscosimeter Comparisons—Factors to Reduce Redwood Time to Saybolt Universal Time or Engler Degrees

Redwood time in seconds	Kinematic viscosity	Saybolt time / Redwood time	Engler degrees / Redwood time	Redwood time in seconds	Kinematic viscosity	Saybolt time / Redwood time	Engler degrees / Redwood time
30	0.0154	1.08	0.0365	80	0.1845	1.16	0.0349
32	.0245	1.09	.0363	85	.1989	1.16	.0349
34	.0332	1.09	.0361	90	.2131	1.17	.0348
36	.0414	1.10	.0360	95	.2272	1.17	.0348
38	.0493	1.10	.0359				
				100	.2412	1.17	.0348
40	.0570	1.11	.0358	110	.2689	1.17	.0347
42	.0645	1.11	.0357	120	.2964	1.17	.0347
44	.0717	1.12	.0357	130	.3236	1.17	.0347
46	.0788	1.12	.0356	140	.3506	1.18	.0347
48	.0854	1.13	.0355				
				150	.3775	1.18	.0347
50	.0924	1.13	.0354	160	.4043	1.18	.0346
55	.1088	1.14	.0354	180	.4576	1.18	.0346
60	.1247	1.14	.0353	200	.5106	1.18	.0346
65	.1401	1.15	.0352	225	.5766	1.18	.0346
70	.1552	1.15	.0351	250	.6425	1.18	.0345
75	.1700	1.16	.0350				

TABLE 6.—Viscosimeter Comparisons—Factors to Reduce Saybolt Universal Time to Engler Degrees or Redwood Time

[For additional values for the first two columns see W. H. Herschel and E. W. Dean, Bureau of Mines, Reports of Investigations, Serial No. 2201, January, 1921.]

Saybolt time in seconds	Kinematic viscosity	Engler degrees / Saybolt time	Redwood time / Saybolt time	Saybolt time in seconds	Kinematic viscosity	Engler degrees / Saybolt time	Redwood time / Sabolt time
32	0.0142	0.0337	0.928	85	0.1658	0.0305	0.862
34	.0219	.0334	.920	90	.1780	.0304	.860
36	.0292	.0332	.914	95	.1901	.0303	.858
38	.0362	.0330	.909	100	.2020	.0302	.856
40	.0430	.0328	.905	110	.2256	.0301	.855
42	.0495	.0326	.901	120	.2490	.0300	.854
44	.0559	.0324	.897	130	.2722	.0299	.853
46	.0621	.0322	.893	140	.2951	.0299	.852
48	.0681	.0319	.889	160	.3408	.0298	.851
50	.0740	.0317	.885	180	.3860	.0297	.850
55	.0883	.0315	.881	200	.4310	.0296	.849
60	.1020	.0313	.871	225	.4870	.0295	.848
65	.1153	.0312	.873	250	.5428	.0294	.847
70	.1283	.0310	.870	300	.6540	.0293	.847
75	.1410	.0308	.867	350	.7648	.0293	.846
80	.1535	.0307	.865	400	.8755	.0292	.846

TABLE 7.—Viscosimeter Comparisons—Factors to Reduce Engler Degrees to Saybolt Universal or Redwood Time

Engler degrees	Kinematic viscosity	Saybolt time / Engler degrees	Redwood time / Engler degrees	Engler degrees	Kinematic viscosity	Saybolt time / Engler degrees	Redwood time / Engler degrees
1.10	0.0166	29.7	27.5	2.30	0.1416	32.8	28.5
1.15	.0234	29.9	27.6	2.40	.1506	32.9	28.5
1.20	.0299	30.1	27.6	2.50	.1593	33.0	28.5
1.25	.0358	30.3	27.7	2.60	.1677	33.1	28.6
1.30	.0420	30.5	27.8	2.70	.1764	33.2	28.6
1.35	.0476	30.7	27.8	2.80	.1849	33.3	28.6
1.40	.0534	30.9	27.9	2.90	.1935	33.4	28.6
1.45	.0590	31.1	27.9	3.00	.2019	33.5	28.7
1.50	.0646	31.3	28.0	3.50	.2432	33.6	28.7
1.60	.0750	31.5	28.1	4.00	.2833	33.7	28.8
1.70	.0853	31.7	28.1	4.50	.3228	33.9	28.8
1.80	.0953	31.9	28.2	5.00	.3624	33.9	28.8
1.90	.1046	32.1	28.3	6.00	.4404	34.0	28.9
2.00	.1143	32.3	28.3	7.00	.518	34.1	28.9
2.10	.1236	32.5	28.4	8.00	.595	34.1	29.9
2.20	.1326	32.6	28.5	9.00	.671	34.2	29.0

TABLE 8.—Viscosimeter Comparisons—Factors to Reduce Engler Time to Saybolt Universal or Redwood Time

Engler time in seconds	Kinematic viscosity	Saybolt time / Engler time	Redwood time / Engler time	Engler time in seconds	Kinematic viscosity	Saybolt time / Engler time	Redwood time / Engler time
56	0.0155	0.578	0.535	130	0.1624	0.641	0.557
58	.0210	.581	.537	140	.1793	.645	.558
60	.0260	.585	.538	150	.1956	.649	.559
62	.0309	.588	.540	160	.2121	.652	.559
64	.0357	.592	.541	180	.2438	.654	.560
66	.0403	.595	.542	200	.2753	.656	.560
68	.0449	.598	.543	225	.3140	.658	.561
70	.0496	.601	.544	250	.3525	.659	.561
75	.0604	.605	.546	275	.3904	.660	.562
80	.0709	.611	.547	300	.4282	.661	.562
85	.0811	.616	.549	325	.4660	.662	.563
90	.0907	.621	.550	350	.5038	.663	.563
95	.1004	.625	.552	375	.5413	.664	.564
100	.1095	.629	.553	400	.5784	.665	.564
110	.1279	.633	.555	500	.7271	.666	.565
120	.1453	.637	.556	600	.8753	.667	.565

WASHINGTON, August 5, 1921.