A DETERMINATION BY THE CONSTANT DEFLECTION METHOD OF THE VALUE OF THE COEFFICIENT OF SLIP FOR ROUGH AND FOR SMOOTH SURFACES IN AIR.

By Leland Johnson Stacy.

Abstract.

Coefficient of slip for rough and smooth surfaces in air, determined by the constant deflection method.—The apparent coefficient of viscosity measured by this exceptionally precise method does not come out constant for the lower pressures unless correction is made for the slip at the surfaces. The relation $\eta_p'(1 + k\zeta_p) = \eta$ = constant, between η_p', the apparent viscosity coefficient, and ζ_p, the coefficient of slip, enables ζ_p to be determined from measurements of η_p' at pressures of 0.2 mm or lower. The apparatus included a vacuum-tight chamber inside which a cylinder of radius 5.341 cm was suspended by a steel wire concentric with a cylinder of radius 6.063 cm which could be rotated at a constant slow rate so as to cause a steady deflection of the inner cylinder. The accuracy of this method of measuring η_p' is so great that the values of $\zeta_{76} = \zeta_p p/76$ all lie within ± 4 per cent of the mean. The chief difficulty was in keeping the air pure because of the gradual evolution of gas, probably hydrogen, inside the apparatus; but by taking observations only shortly after evacuation this effect was avoided. *For brass surfaces*, ζ, reduced to 23° and 76 cm, came out 66.15×10^{-7} which is practically the theoretical minimum deduced by Millikan for a completely diffusing surface, 65.9×10^{-7}. *For surfaces coated with shellac*, the coefficient was found to be 97×10^{-7} for a fresh surface, in agreement with the value obtained by Lee from droplet measurements, but it decreased steadily with time, presumably because of a roughening due to oxidation, falling in two months to within 3 per cent of the theoretical minimum. The early part of this work was done in collaboration with E. L. Harrington.

Coefficient of viscosity of air at 0.1 mm is the same as at atmospheric pressure when correction is made for the slip effect. The constancy of the values obtained for ζ provides new evidence that the coefficient is independent of the pressure.

I. Historical Development of the Idea of Slip.

The theory that the coefficient of viscosity of a gas should be independent of the pressure was first deduced by Maxwell[1] from a consideration of the internal friction of molecules assumed to be rigid spheres. He first deduced the relation

$$(1) \qquad \eta = \rho \bar{c} l,$$

where η = coefficient of viscosity; ρ = density of the gas; $\bar{c}$ = mean

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[1] Phil. Mag., 1860, Vol. 19, p. 31.

molecular velocity; l = mean free path of gas molecule. Since the density is directly proportional to the pressure, while the mean free path is inversely proportional to the same quantity, the product ρl, and therefore η, should be independent of the pressure.[1] In a later paper,[2] Maxwell reported some experimental tests of his theory for pressures ranging from 30 in. to 0.5 in. of mercury. His apparatus consisted of a torsion pendulum of three plane-parallel plates suspended by an elastic fiber between four fixed plane-parallel plates. The whole system was enclosed in an airtight vessel and the logarithmic decrement of the oscillations was observed for different pressures. He found no observable change in the decrement, which is a measure of the viscosity, within the pressure range studied.

The same relation (1) was derived later by O. E. Meyer.[3] By an experimental arrangement similar to Maxwell's he checked the theoretical deductions for the same range of pressures. Results at pressures below 1/60 atmosphere showed a falling off of the viscosity coefficient, which he later ascribed to the fact that, in the theory of the experimental method, the external friction (ϵ) has been considered infinitely large in comparison with the internal friction or viscosity. Thus he introduced into the Kinetic Theory of Gases the slip coefficient $\zeta = \eta/\epsilon$, which Helmholtz[4] had previously defined for liquids.

II. Determinations of the Coefficient of Slip in Air.

The first experimental determination of the value of the coefficient of slip was made by Kundt and Warburg[5] who used the capillary tube method. Their results were:

Tube No.	Pressure.	Temperature.	ζ.	$\zeta_{76} = \dfrac{\zeta \cdot p}{76}$.
1	33.8 mm	15° C	.00017	76×10^{-7}
2	39.0 "	15° C	.00016	82×10^{-7}
2	33.8 "	15° C	.00018	80×10^{-7}
			Mean	79×10^{-7}

The mean of their values at 15° C and 76 cm is about 79×10^{-7}. Millikan in a preceding article has reduced this to 23° C, getting ζ_{76} at 23° C = 82×10^{-7}.

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[1] Using Stokes' value $\sqrt{\eta/\rho} = .116$ for air, Maxwell made the first calculation of the mean free path of a gas molecule.

[2] Phil. Trans., 1866, Vol. 156, p. 249.

[3] Pogg. Ann., 1865, Vol. 125, p. 177.

[4] Wiener Sitzung., 1860, Vol. 40, p. 607.

[5] Pogg. Ann., 1876, Vol. 159, p. 399.

In the determination of the elementary electrical charge by the falling drop method Millikan[1] found that very small droplets of oil did not follow Stokes' equation

$$v = \frac{2}{9}\frac{ga^2}{\eta}(\sigma - \rho). \tag{2}$$

From his observations he made an empirical correction of the above equation, writing the corrected law in the form

$$v = \frac{2}{9}\frac{ga^2}{\eta}(\sigma - \rho)\left(1 + \frac{Al}{a}\right), \tag{3}$$

where Al was determined from the curve of his observations. Millikan pointed out that the correction of Stokes' Law for Slip[2] gave

$$v = \frac{2}{9}\frac{ga^2}{\eta}(\sigma - \rho)\left(\frac{1 + 3\zeta/a}{1 + 2\zeta/a}\right), \tag{4}$$

which, for small values of ζ/a, reduces to

$$v = \frac{2}{9}\frac{ga^2}{\eta}(\sigma - \rho)(1 + \zeta/a). \tag{5}$$

Thus, the Al determined by Millikan was really the coefficient of slip for oil and air. His value for 23° C was $\zeta_{76} = 77 \times 10^{-7}$. In a later determination[3] a more detailed study of the failure of Stokes' Law for small oil drops gave the value ζ_{76} at 23° C $= 82.2 \times 10^{-7}$.

For small drops of shellac, Lee[4] observed $Al = \zeta_{76}$ at 76 cm and 23° C to be 100×10^{-7}.

These experimental results led Millikan to a theoretical study of slip for different boundary conditions. He concluded that when no gas molecules were regularly reflected after impact upon the walls, the maximum of external friction, and hence the minimum of slip, would result. For a mechanically rough surface, which would cause such diffuse reflection of all gas molecules, he calculated the minimum value of ζ at 23° C and 76 cm to be 65.9×10^{-7}.

III. Theory for Slip Determinations by the Constant Deflection Method.

The theory of the Constant Deflection Method of determining viscosity coefficients gives

$$\eta = \frac{\pi I \phi}{\omega l T^2}\left(\frac{b^2 - a^2}{a^2 b^2}\right). \tag{6}$$

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[1] Phys. Rev., 1911, 32, 382.

[2] Bassett, Hydrodynamics, Vol. II., p. 271.

[3] Phys. Rev., 1913, Vol. II., p. 139.

[4] Phys. Rev., 1914, IV., 420.

I = moment of inertia of suspended cylinder; ϕ = angular displacement of suspended cylinder; a = radius of suspended cylinder; l = length of suspended cylinder; T = period of oscillation of suspended cylinder; ω = angular velocity of outer cylinder; b = radius of outer cylinder, when it is assumed that there is no slip at the surfaces of the cylinders. At ordinary pressures, this assumption involves an error too small to be observed by this method. For the case where slip becomes appreciable the complete equation as developed by Millikan is

$$\eta = \frac{\pi I \phi}{\omega l T^2}\left(\frac{b^2 - a^2}{a^2 b^2}\right)\left(1 + 2\zeta_p \frac{b^3 + a^3}{ab^3 - a^3 b}\right). \tag{7}$$

The slip term at atmospheric pressure may be calculated for this apparatus since $a = 5.3412$ cm, $b = 6.0632$ cm, and $\zeta_{76} = 66 \times 10^{-7}$ (from theory). This gives a value for the term

$$2\zeta_p \frac{b^3 + a^3}{ab^3 - a^3 b} = .00002$$

which is quite negligible, since the experimental error is about .1 per cent. Hereafter the equation (6) will be written

$$\eta_p' = \frac{\pi I \phi}{\omega l T^2}\left(\frac{b^2 - a^2}{a^2 b^2}\right) \tag{8}$$

and η_p' defined as the apparent viscosity coefficient at the pressure p.

The value η_{76}' will be taken as the true value of the viscosity coefficient. Equation (7) may now be written

$$\eta = \eta_p'\left(1 + 2\zeta_p \frac{b^3 + a^3}{ab^3 - a^3 b}\right) \tag{9}$$

and solving for ζ_p

$$\zeta_p = \left(\frac{\eta}{\eta'_p} - 1\right)\frac{1}{k}; \qquad k = 2\left(\frac{b^3 + a^3}{ab^3 - a^3 b}\right). \tag{10}$$

Thus to determine the slip coefficient by this method it is necessary, first, to determine the coefficient of viscosity ($\eta = \eta_{76}'$) and then η_p' at some other pressure. Application of equation (10) gives ζ_p, and ζ_{76} is calculated from the formula $\zeta_{76} = \zeta_p(p/76)$. η' and η_p' must, of course, be observed at the same temperature or reduced to the same conditions by the proper formula.

The investigation of slip coefficients by this method was undertaken, at Prof. Millikan's suggestion, by E. L. Harrington[1] to determine whether the slip depended on the nature of the surface as the lack of

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[1] Phys. Rev., 1916, VIII., p. 738.

agreement between the values for oil and shellac drops had indicated. Harrington devoted his time chiefly, however, to the improvement of the precision of the method of determining the viscosity coefficient, leaving the writer to carry on the slip determinations. The writer assisted Harrington for a short time in the first determinations of the slip coefficient. Some of Harrington's results will be included in this paper.

IV. Adaptation of the Apparatus for Slip Determinations.

The Constant Deflection Apparatus consists essentially of two concentric brass cylinders, the inner, *I*, being suspended on an elastic suspension, *s*, so that, when the outer cylinder, *O*, is driven at a constant speed by a clock driving mechanism, *K*, a constant torque due to viscosity will cause a constant deflection of the suspended cylinder from its equilibrium position. To eliminate end effects the inner cylinder is suspended between two guard rings, *G*, of the same diameter and less than .3 mm from it. A small mirror mounted at the base of the suspension wire makes it possible to observe the deflection by a telescope and scale. The period of rotation ($t = 2\pi/\omega$) of the outer cylinder was determined by a chronograph attached to the driving mechanism.

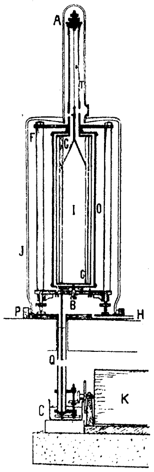

Fig. 1.

The constants of the apparatus as determined by Harrington were used.

Moment of inertia of inner cylinder	$I = 7617.3$
Radius of inner cylinder	$a = 5.3410$ cm
Length of inner cylinder	$l = 24.88$ cm
Radius of outer cylinder	$b = 6.0632$ cm

For work at low pressures, the cylinders were set upon a steel plate, *P*, about 30 cm in diameter. A large-mouthed glass bottle, *J*, about 28 cm in diameter and 62 cm high was found and the mouth ground plane to fit tightly a rubber gasket laid on the steel base-plate. An opening was ground in the bottom of the bottle for the suspension head, *T*, which projected some 25 cm above the large bottle. A glass tube, *A*, sealed at the top was fitted by a ground glass joint into the bottom of the large bottle thus closing the apparatus. A plate glass observing window was sealed over a small hole in the side of the suspension cover to prevent distortion of the image seen in the observing mirror. A discharge tube for spectroscopic work was also sealed into the side of the suspension cover. The driving shaft for the rotating cylinder was led through an iron pipe, *Q*, sealed into the steel base-plate. The lower end of this pipe was immersed in a vessel of mercury, *C*, thus sealing it from the outside. A rim around the edge of the base-plate made it possible to use a mercury seal at this joint and, the bottom of the bottle being somewhat concave, a mercury seal was also used at the upper joint. Thus the apparatus was enclosed tightly enough to permit evacuation to about .001 mm pressure.

A Gaede mercury pump backed by a rotary oil pump made it possible to reduce the pressure within the apparatus to .1 mm in a little over two hours. The volume of the apparatus was about 150 liters. Pressures were read by a McLeod gauge calibrated to read .0001 mm. Temperatures within the apparatus were read from a Beckmann thermometer which had been calibrated by comparison with a standard Baudin instrument. The observing telescope and scale were mounted about 200 cm distant from the suspended mirror and the deflection could be read to .1 mm. The steel suspension wire used throughout this work gave an observed scale deflection of 62 to 64 cm when the period of rotation of the outer cylinder was about 30 sec.

V. Experimental Methods and Elimination of Errors.

The determination of the viscosity coefficient was made from the formula

$$\eta_p' = K\frac{t}{T^2}\tan^{-1}\frac{s}{2d} \qquad \text{where} \qquad t = \frac{2\pi}{\omega}\,; \qquad \phi = \tan^{-1}\frac{s}{2d},$$

$$K = I\left(\frac{b^2 - a^2}{2a^2b^2l}\right).$$

The period T and the scale distance d being determined beforehand, it was only necessary to observe s and t so that η_p' could be calculated. Temperatures and pressures were read as already described.

Having determined $\eta_{76}'(=\eta)$, it was necessary to determine η_p' at some low pressure and calculate ζ_{76} from the equations

$$\zeta_p = \left(\frac{\eta}{\eta_p'} - 1\right)\frac{1}{k} \qquad \text{and} \qquad \zeta_{76} = \frac{\zeta_p \cdot p}{76}.$$

For atmospheric pressure the observed scale deflection s was about 63 cm with an error of .3 mm. At 0.12 mm pressure and $t = 30$ sec. the scale deflection was found to be about 56 cm. Thus a difference of 7 cm with an error of .3 mm in reading would give an apparent error of not more than 1 part in 200. The gauge reading to .0001 mm, this error should be only 1 part in 1,200. Errors in observing all the other factors were much less than these, so they may be neglected. It was found, however, that the principal source of inaccuracy was due to change of the pressure during observations. This rise of pressure was considerable in the first few hours after evacuation was stopped, but reached a steady value after 24 hours or so. It was found by experiment that during the 10-minute interval necessary for one complete observation the pressure change was from .001 to .003 mm. After one or two days the pressure rose less than that in 24 hours. This was explained by supposing the increase in pressure to be due to gases released from the glass and metal surfaces. By taking pressure readings before and after each observation a fairly accurate mean value was obtained. The temperature was also read at frequent intervals and the mean value used. The apparatus being set up in a constant temperature room, the observations were made within a very narrow range (22° to 24° C). Variations from 23° C were corrected for by Millikan's formula (Ann. der Physik, 1913, Vol. 41, p. 759).

$$\eta_\theta = \eta_{23^\circ} - .000000493(23^\circ - \theta).$$

In the early work on slip determinations, a series of observations was made after a single evacuation. The values of ζ_{76} calculated from these observations gave an initial value of about 70×10^{-7} but rose steadily until a value of 200×10^{-7} was found about two weeks later. The pressure change was from .1238 to .1448 mm during this interval. Since ζ_{76} should be independent of the pressure, this indicates that the increase in pressure must be due to the presence of some gas of a lower viscosity than air. This suggested that hydrogen (viscosity about one half that of air) was being released from occlusion by the metal parts of the apparatus. Spectroscopic examination of the discharge tube showed a definite increase in the intensity of the hydrogen lines when the apparatus was allowed to stand several days at a low pressure.

Admission of air to full atmospheric pressure to flush out the apparatus and a second evacuation gave the same result, viz., a low value during the first two or three hours after the pumps were stopped, then a steady rise in the value of the slip constant ζ_{76}. To eliminate this variation it was found advisable to admit air immediately after a set of observations was completed and to evacuate only a short time before readings were to be taken. Thus the time during which the "hydrogen effect" might be present was so short that it did not affect the results appreciably. It was found that the values of ζ_{76} obtained within three or four hours after an evacuation were quite consistent. Observations were usually made within an hour after evacuation. After many evacuations this "hydrogen effect" was less marked but was always present. By taking observations shortly after evacuation, it was avoided.

VI. TABLE OF OBSERVATIONS AND CALCULATED DATA FOR BRASS SURFACES IN AIR.

Results on Brass Surfaces in Air.

$d = 200.5$ cm; $T = 175.48$; $\eta = 1822.6 \times 10^{-7}$.

S (cm).	t (sec.).	θ (° C).	$\eta_p \times 10^7$.	$\zeta_p \times 10^5$.	p (mm).	$\zeta_{76} \times 10^7$.
56.28....	30.134	23.04	1643.0	3884	.1303	66.6
56.56....	30.040	23.05	1646.0	3811	.1328	66.6
56.71....	30.034	22.76	1649.4	3701	.1361	66.4
56.93....	29.989	22.81	1653.2	3616	.1388	66.0
57.23....	29.500	22.67	1634.7	4044	.1238	65.9
55.95....	30.267	22.67	1640.2	3912	.1266	65.2
56.76....	29.992	22.72	1646.0	3726	.1340	65.7
56.63....	30.124	22.72	1646.2	3721	.1362	66.7
55.77....	30.187	22.81	1628.2	4166	.1200	65.8
56.25....	29.975	22.82	1630.6	4107	.1209	65.3
57.25....	29.720	23.70	1645.0	3856	.1253	63.6
57.02....	29.880	23.66	1647.1	3797	.1268	63.4
57.10....	29.795	22.81	1644.8	3764	.1287	63.8
56.68....	30.032	22.81	1645.9	3738	.1311	64.5
56.71....	30.134	22.80	1652.9	3570	.1361	63.9
56.86....	30.079	22.83	1653.8	3556	.1367	64.0
57.20....	29.929	22.82	1655.1	3520	.1405	65.1
57.27....	29.922	22.79	1656.7	3480	.1428	65.4
57.15....	30.000	22.80	1657.6	3459	.1445	65.8
57.05....	30.053	22.73	1657.7	3451	.1459	66.2
57.32....	29.922	22.79	1656.2	3437	.1467	66.3
57.30....	29.930	22.77	1656.5	3444	.1475	66.8
56.51....	29.952	22.87	1640.5	3836	.1368	69.0
55.77....	29.917	22.84	1614.0	4469	.1178	69.3
55.65....	30.000	22.78	1614.6	4436	.1166	68.1
56.47....	29.873	22.90	1631.2	4053	.1300	69.3
56.53....	30.037	22.42	1641.9	3733	.1402	68.9
56.73....	30.043	23.01	1651.4	3405	.1508	67.6
56.62....	29.915	22.73	1637.0	3886	.1343	68.7
56.68....	30.102	22.84	1649.8	3591	.1349	63.7
56.46....	30.100	22.81	1647.1	3646	.1378	66.1
56.76....	30.018	22.79	1647.4	3630	.1424	68.0
56.68....	29.972	22.87	1642.6	3762	.1308	64.7
57.00....	29.860	22.99	1645.6	3710	.1338	65.3
57.03....	30.158	23.33	1662.9	3338	.1558	68.3
56.34....	30.080	23.46	1638.8	3915	.1258	64.8
Mean ...						66.15

The observations were made within a pressure range of .1 to .18 mm since at lower pressures the error due to change of pressure during an observation was large, while at pressures above .18 mm the deflection *s* differed so little from the deflection at atmospheric pressure that the error of observing this difference became considerable.

In general, the experimental conditions were as follows:

Temperature — 22° C to 24° C
Pressure — .1000 mm to .1800 mm
Period (t) — 30 sec. (±.2)
Period (T) — 175.5 sec.

$$\left.\begin{array}{lrl} \text{Scale deflection, for } p = & 76 & \text{cm} - 630 \text{ mm} \\ \text{"} \quad p = & 0.18 & \text{mm} - 580 \text{ mm} \\ \text{"} \quad p = & 0.10 & \text{mm} - 550 \text{ mm} \end{array}\right\} \text{approximately}$$

Observations were usually made in pairs within an hour after evacuation.

The mean value (66.15×10^{-7}) is very close to Millikan's theoretical minimum value (65.9×10^{7}) but is considerably lower than any of the values found by other methods for oil or for glass surfaces.

VII. Determination of Slip for Shellac Surfaces in Air.

The cylinders were next coated with a thin layer of shellac, dried by an air blast and replaced in position. From the weight of the cylinders before and after the shellac was applied and the surface area of the cylinders, the average thickness of the shellac film was calculated. This was found to be .01 mm and made only a small correction in the values of the constants a and b.

After the determination of the viscosity coefficient at atmospheric pressure, the pressure was reduced and observations made as before. At first a high value of $\zeta_{76} = 97 \times 10^{-7}$ was found while the shellac was fresh. Later, the values of ζ_{76} dropped steadily toward the minimum value. This result is shown in the two sets of data here given; the first set of observations being due to Harrington and the second to the writer. In two other trials, accidental experimental difficulties prevented the writer from making observations while the shellac was fresh but values between 80 and 90×10^{-7} were found several days after application of the shellac. The fall in the observed value of the slip coefficient indicates a change in the surface due probably to oxidation of the shellac which seems to produce a rough surface.

Data on Fresh Shellac Surfaces in Air.

$d = 200.6$, $T = 176.00$.

E. L. Harrington: Fresh Shellac, August 1, 1916.

Date.	S.	t.	θ.	$\eta_p' \times 10^7$.	$\zeta_p \times 10^5$.	p (mm).	$\zeta_{76} \times 10^7$.
Aug. 9........	55.93	29.719	23.38	1602.8	4911	.1474	95.2
	55.72	29.727	23.44	1597.3	5059	.1478	98.5
Aug. 10, A.M..	53.42	29.715	23.76	1531.3	6842	.1048	94.3
	52.55	29.960	23.86	1519.4	7188	.1058	100.0
Aug. 10, P.M..	53.99	29.936	23.67	1559.0	6080	.1125	90.0
	53.19	30.263	23.60	1552.9	6240	.1133	93.0
Aug. 11, A.M..	53.43	30.227	23.46	1556.6	6121	.1107	89.0
	52.96	30.440	23.50	1553.9	6204	.1112	90.8
Aug. 11, P.M..	55.19	30.100	23.13	1602.0	4886	.1288	82.8
	55.14	30.100	23.13	1600.5	4920	.1298	84.1
Aug. 12.......	56.94	29.827	23.64	1637.0	4099	.1438	77.6
	56.75	29.917	23.70	1636.5	4108	.1438	77.7
Aug. 30.......	57.28	29.780	23.10	1653.1	3538	.1506	70.1

L. J. Stacy: Fresh Shellac, March 7, 1917.

Mar. 9, A.M..	56.04	29.789	23.36	1578.8	5588	.1330	97.7
	55.92	30.010	23.40	1582.5	5381	.1352	95.7
Mar. 9, P.M..	57.66	29.800	23.14	1619.7	4580	.1470	88.6
	57.26	30.080	23.19	1623.7	4486	.1482	87.5
Mar. 10, A.M..	58.15	29.723	23.55	1628.2	4414	.1418	82.3
	57.76	29.983	23.59	1632.4	4318	.1441	81.9
Mar. 10, P.M..	57.56	30.164	23.53	1636.7	4206	.1493	82.6
	58.12	29.896	23.50	1637.7	4179	.1543	84.8
	57.30	30.322	23.24	1637.9	4152	.1545	84.4
Mar. 11.......	56.83	29.985	22.87	1606.6	4876	.1313	84.2
	56.06	30.432	22.86	1608.7	4820	.1323	83.9
Mar. 12.......	57.38	30.334	23.12	1640.8	4066	.1487	79.5
	57.77	30.188	23.21	1643.8	3999	.1495	78.7
Mar. 13.......	57.75	30.144	23.52	1640.9	4102	.1443	77.9
	58.05	30.031	23.52	1643.1	4048	.1473	78.4
Mar. 16.......	58.16	30.169	23.07	1653.7	3747	.1518	74.8
Mar. 17.......	57.42	30.084	22.85	1628.4	4242	.1332	74.3

The following results were obtained using the same experimental method as with brass surfaces. The shellac surfaces were about two months old when the first readings were taken.

The results of these experiments furnish independent evidence of the fact that the viscosity of a gas is independent of the pressure, since ζ_{76} turns out to be a constant for a given surface in air. The value of ζ_{76} for rough surfaces checks Millikan's theoretically deduced values within the limit of error of the experiment. The variation in slip for different surfaces has been checked and the result for fresh shellac, $\zeta_{76} = 96.8 \times 10^{-7}$, is very close to the result Lee obtained, $\zeta_{76} = 100 \times 10^{-7}$, from the correction of Stokes' Law for falling shellac drops.

In conclusion the writer wishes to express his indebtedness to Professor R. A. Millikan who suggested the problem and directed the experimental

Data for Old Shellac Surfaces in Air.
d = 200.6 cm; T = 176.00 sec.

S.	t.	θ.	$\eta_p' \times 10^7$.	$\zeta_p \times 10^5$.	p (mm).	$\zeta_{76} \times 10^7$.
55.39....	30.027	23.67	1605.1	4833	.1088	69.2
57.49....	29.767	24.28	1648.5	3875	.1338	68.2
57.06....	30.076	24.34	1653.3	3767	.1370	67.9
57.49....	30.023	23.11	1661.5	3443	.1535	69.5
57.02....	30.058	22.76	1653.8	3639	.1444	69.1
57.20....	30.123	22.87	1662.5	3431	.1478	66.7
57.38....	30.023	22.90	1661.7	3447	.1488	67.5
57.28....	30.074	22.95	1662.1	3444	.1493	67.7
57.64....	29.885	22.92	1659.2	3507	.1478	68.2
57.72....	29.930	22.97	1664.4	3392	.1495	66.7
57.44....	30.144	23.08	1668.9	3299	.1573	68.3
57.60....	30.050	23.11	1668.2	3317	.1585	69.2
56.75....	30.111	23.24	1647.3	3830	.1351	68.1
56.90....	30.112	23.28	1651.1	3744	.1373	67.6
57.13....	30.067	23.21	1656.0	3613	.1437	68.3
55.19....	30.014	23.06	1597.2	5032	.1057	70.0
55.23....	30.087	23.10	1602.3	4910	.1076	69.5
57.15....	30.210	23.57	1664.0	3464	.1498	68.3
57.27....	30.271	23.66	1670.8	3316	.1533	66.9
56.91....	30.211	23.21	1657.2	3585	.1411	66.6
57.17....	30.174	23.31	1662.6	3469	.1445	66.0
57.36....	29.963	22.55	1650.5	3823	.1353	68.1
57.37....	30.019	22.58	1652.8	3793	.1380	68.6
56.74....	30.300	22.51	1644.5	3780	.1288	64.1
57.33....	30.161	22.87	1655.3	3742	.1356	66.8
57.25....	30.160	22.86	1652.6	3806	.1364	68.3
58.38....	29.508	21.94	1647.3	3835	.1363	68.8
57.23....	30.152	22.12	1655.5	3777	.1373	68.2
Mean ...						67.7

This result is $2\frac{1}{2}$ per cent higher than the value found for brass surfaces in air.

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[1] The work described in this paper was completed in February 1919.