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RISE OF AIR BUBBLES IN AIRCRAFT LUBRICATING OILS

By J. V. Robinson

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SUMMARY

Lubricating and antifoaming additives in aircraft lubricating oils may impede the escape of small bubbles from the oil by forming shells of liquid with a quasi-solid or gel structure around the bubbles.

The rates of rise of small air bubbles, up to 2 millimeters in diameter, were measured at room temperature in an undoped oil, in the same oil containing foam inhibitors, and in an oil containing lubricating additives. The apparent diameter of the air bubbles was measured visually through an ocular micrometer on a traveling telescope.

The bubbles in the undoped oil obeyed Stokes' Law, the rate of rise being proportional to the square of the apparent diameter and inversely proportional to the viscosity of the oil.

The bubbles in the oils containing lubricating additives or foam inhibitors rose more slowly than the rate predicted by Stokes' Law from the apparent diameter, and the rate of rise decreased as the length of path the bubbles traveled increased.

A method is derived to calculate the thickness of the liquid shell which would have to move with the bubbles in the doped oils to account for the abnormally slow velocity. The maximum thickness of this shell, calculated from the velocities observed, was equal to the bubble radius.

INTRODUCTION

The addition of Dow Corning Fluid and certain other foam inhibitors to aircraft lubricating oil was observed to increase the stability of a residue of "emulsified" air in an oil, which was being rapidly circulated and continuously aerated (reference 1). In the reference cited, experiments are described showing that, while the escape of most of the "emulsified" air in the oil was facilitated by the presence of foam inhibitors, by the mechanism of bubble coalescence, and, while a foam head was nearly eliminated, a residue representing a small percentage of the original aeration was actually stabilized in the oil as an "air emulsion" and as a collar on the surface of the oil. It was supposed that the air bubbles in the stabilized "air emulsion" were protected from coalescence by a complete film of the foam inhibitor spread upon their inner surface. In the same series of experiments, it was observed that an oil containing lubricating additives likewise stabilized "emulsified air."

It was the purpose of the experiments described in this report to expose the mechanism by which the additives in the lubricating oil stabilized the emulsified air incorporated into the oil circulated through a high-speed gear pump. By measuring the velocity of rise of air bubbles in a column of quiescent oil, with and without additives, the presence or absence of thick layers of liquid on the bubble surface and moving with the bubbles could be ascertained. The presence of such thick layers of liquid moving with the bubbles in oils containing additives is demonstrated in the experiments described in this report, and their absence demonstrated in an undoped oil.

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SYMBOLS

V	velocity of fall of spherical body in viscous medium $\left(V = \frac{2ga^2(d_1 - d_2)}{9\eta}\right)$, centimeters per second
g	acceleration of gravity (980 cm/sec/sec or dynes/g)
a	radius of spherical body, centimeters
d_1	density of spherical body, grams per cubic centimeter
d_2	density of medium, grams per cubic centimeter
η	absolute viscosity of medium, poises
d_o	density of oil (0.9 g/cc at 25° C)
d_a	density of air (0.00129 g/cc at 25° C)
d_{ao}	effective density of air bubble surrounded by a rigid shell of oil

r_a, D_a	radius and diameter, respectively, of air bubble, measured optically
r_a', D_a'	radius and diameter, respectively, of air bubble, calculated from Stokes' Law from its observed velocity of rise
r_{ao}, D_{ao}	radius and diameter, respectively, of rigid shell of oil surrounding air bubble
v_a	volume of air bubble $\left(v_a = \frac{4}{3}\pi r_a{}^3\right)$
v_o	volume of rigid oil shell around air bubble
$v_{ao} = v_a + v_o$	
ν	kinematic viscosity of liquid medium or oil $(\nu = \eta/d_2$ or $\nu = \eta/d_o)$, stokes

THEORY OF RISE OF AIR BUBBLES THROUGH OIL

The rate of fall of a spherical body through a viscous and homogeneous medium is related by Stokes' Law to the radius and density of the spherical body and to the viscosity and density of the medium. Stokes' Law is expressed by the formula

$$V = \frac{2ga^2(d_1 - d_2)}{9\eta}$$

Applying the formula to the rise of air bubbles through lubricating oil, the constants of the formula may be evaluated: d_1 becomes d_a, d_2 becomes d_o, and a becomes r_a'. Since $d_o \gg d_a$, $d_a - d_o$ is equal to $-d_o$, with an error of about 0.1 percent. Since the equation was derived for falling bodies, the velocity of rising bodies is negative. The difference in densities is also negative; hence all quantities in the computation are reckoned as positive. Solving the equation, $(r_a')^2 = 9\eta V/2gd_o$. Since η/d_o is equal to ν, the kinematic viscosity of the oil $(r_a')^2 = 9\nu V/2g$; and, substituting the bubble diameter for its radius, $(D_a')^2 = 18\nu V/g = 0.01836\nu V$.

The observed rise of the air bubbles appeared to follow Stokes' Law, in that the variation of the velocity of rise was nearly linear with the square of the observed diameter, as is demonstrated by the data of this report. However, in doped oils, the bubbles rose abnormally slowly. This is explained by assuming that the air bubble is accompanied by a shell of oil (or additive, or both) which rises through the oil with the bubble. The resistance to passage of the bubble is increased by the presence of the shell, with no compensating increase in the oil displacement.

Consider an air bubble rising through oil and carrying with it a rigid shell of oil. It is desired to calculate the radius of this shell. The effective density of the bubble with its shell is then

$$d_{ao} = \frac{v_a d_a + v_o d_o}{v_{ao}}$$

or

$$d_{ao} = \frac{v_a d_a}{v_{ao}} + \frac{v_o d_o}{v_{ao}}$$

Considering the bubble as truly spherical (i.e., undistorted by the velocity pressure against its front),

$$v_a = \frac{4}{3} \pi r_a{}^3$$

$$v_{ao} = \frac{4}{3} \pi r_{ao}{}^3$$

and

$$v_o = \frac{4}{3} \pi \left(r_{ao}{}^3 - r_a{}^3\right)$$

The effective density becomes, on substitution of these values,

$$d_{ao} = \frac{r_a{}^3 d_a}{r^3{}_{ao}} + \frac{\left(r_{ao}{}^3 - r_a{}^3\right) d_o}{r_{ao}{}^3} = \left(d_a - d_o\right)\frac{r_a{}^3}{r_{ao}{}^3} + d_o$$

The a in Stokes' Law is now r_{ao}, d_1 becomes d_o, and d_2 becomes d_{ao}; hence,

$$V = \frac{2gr_{ao}^2(d_o - d_{ao})}{9\eta}$$

Substituting the expression for d_{ao} derived above and simplifying algebraically gives

$$V = \frac{2g(d_o - d_a)r_a^3}{9\eta r_{ao}}$$

Solving,

$$r_{ao} = \frac{2g(d_o - d_a)r_a^3}{9\eta V}$$

As noted before, the difference in densities $d_o - d_a$ may be considered equal to d_o with sufficient accuracy, and the kinematic viscosity ν may then be substituted for η/d_o. These substitutions give

$$r_{ao} = \frac{2gr_a^3}{9\nu V}$$

It will be noted that this equation contains the expression $\frac{2g}{9\nu V}$ which is the reciprocal of the quantity already equated to $(r_a')^2$. The result may finally be expressed in the form

$$r_{ao} = \frac{r_a^3}{(r_a')^2}$$

Stating this result in words, it has been shown that the radius of the rigid shell of oil carried along by the air bubble is equal to the cube of the actual radius of the air bubble, divided by the square of the radius calculated from the observed velocity of rise, substituted uncritically into Stokes' Law.

It hardly needs to be pointed out that the same relation is true for the diameters, that is,

$$D_{ao} = \frac{D_a^3}{(D_a')^2}$$

A convenient method of analyzing the experimental results is suggested; the ratio of the squares of the diameters observed and calculated

$$\frac{D_a^2}{(D_a')^2}$$

is the factor by which the observed diameter should be multiplied to obtain the outside diameter of the rigid shell of liquid carried by the air bubble. The proportion of this shell is thus indicated for any size of bubble. As derived on a preceding page, the calculated diameter of a bubble, in a given oil of known viscosity, is equal to a factor times the observed velocity of rise.

APPARATUS

The oil was contained in a 100-milliliter graduated cylinder. The markings on the side of the cylinder, at 10-milliliter intervals, were used as reference lines to indicate vertical distance. In the first series of experiments, the cylinder stood in the open laboratory, but more uniform temperature was obtained in later experiments by standing it in a large reservoir of water.

The temperature of the oil was measured by a thermometer, graduated in $\frac{1}{10}^{\circ}$ C, which was immersed in the oil in the cylinder. In the series of experiments with the cylinder standing in air, the bubbles were timed between the graduations just above and below the thermometer bulb, in an effort to minimize the effect of temperature gradients in the oil. Because of the necessity for strong illumination, the oil absorbed radiant energy and its temperature was generally somewhat above the temperature of the surrounding air. With the cylinder immersed in water, the temperature changed very slowly, and the entire visible length of the cylinder was used.

The reservoir used to jacket the cylinder in the later experiments was made of sheet metal, its bottom being about 18 by 24 inches in dimensions. It was filled with water until the level stood about 1 inch below the top of the graduated cylinder standing inside. Glass windows were set with gaskets in the long sides of the reservoir, permitting illumination from one side, and observation from the other. The windows were about 4 inches wide by 6 inches tall, of plate glass. Black paper was pasted on the front window, except for a vertical strip in the center, permitting the cylinder to be viewed but shielding the eyes from excess light.

Illumination was provided by an ordinary 100-watt lamp placed next to the back window of the reservoir.

Bubble diameter was measured by visual comparison of the bubble image magnified about 10 times by a traveling telescope with the lines of an ocular micrometer net in the telescope. The telescope was also used to measure the vertical distance between the graduations on the cylinder. The ocular net was calibrated by comparison with a stage micrometer slide.

Bubbles were formed in a capillary tube, with a U-turn on the end, which was inserted to the bottom of the cylinder. A small syringe pipette was connected with rubber tubing to the upper end of the capillary, and bubbles were ejected from the tip of the U-tube, under the oil, by pushing in the plunger. The capillary was clamped in place, as the position of the jet was critical. The jet could not be far from the wall of the cylinder, because the outlines of the bubbles would not be sharp, and it could not be too close to the wall, because the wall would interfere with the free rise of the bubbles. For convenience, the jet was set at the 10-milliliter graduation of the cylinder.

TEST PROCEDURE

The cylinder was filled with oil, to the 100-milliliter mark. The capillary tube with syringe pipette attached was inserted into the oil and clamped in place, the top of the jet being set even with the 10-milliliter graduation on the cylinder. The cylinder was alined in front of the observation window of the reservoir, in those experiments where the cylinder was jacketed. The thermometer was inserted into the oil, and clamped in place with the bulb just below the middle of the graduated portion of the cylinder.

Bubbles were formed by pushing in the plunger in the syringe pipette. Oil backed up into the capillary, cutting off small "slugs" of air. The size of the bubble could be estimated by the length of the slug in the capillary tube, and by manipulation bubbles of any approximate diameter desired could be ejected.

Two stop watches were used in those experiments where the rate of rise of the bubble was measured over different intervals of its whole journey through the oil. One watch was started when the bubble crossed the 20-milliliter graduation; when the bubble crossed the 30-milliliter graduation, the first watch was stopped and the second watch simultaneously started. The time indicated by the first watch was immediately recorded and the watch hand returned to the starting position, ready to be started again at the instant the bubble crossed the 40-milliliter graduation. The process was continued until the bubble reached the 80-milliliter graduation, at which point it came to the end of the window in the reservoir and went out of sight.

In the early experiments, the bubble was timed only in the central portion of its travel, between the 30- and 60-milliliter graduations, in the center of which the thermometer bulb was placed. In the tables of data, it is obvious which method was used. Sometimes, with very small bubbles, the time required for the bubble to cross the field of the telescope (0.19 cm) was measured rather than the time between two graduations.

Whenever time permitted, the telescope was focussed on the rising bubble, and the diameter noted against the ocular micrometer net. In the case of large bubbles, this was possible only once or twice during their rise, and required very rapid manipulation. With small bubbles, there was ample time for the observation, and the diameter was measured between each pair of graduations.

The thermometer was read before and after the rise of each bubble, when the cylinder was not jacketed, and less frequently when the cylinder was immersed in the reservoir of water.

PRECISION

The over-all precision of the measurements cannot be evaluated except in terms of a statistical study, which is neither justified nor possible with the present data. However, certain of the variables may well be considered separately.

The diameter of the bubbles was measured by estimation of the size of the image against a calibrated ocular net micrometer. Each square of the net corresponds to 0.0190 centimeter of object size. The diameters were estimated to one-tenth of a square, with an estimated precision of about plus or minus one-tenth of a square. An error of ±0.002 centimeter is indicated, which is less than 5 percent of the smallest bubble measured.

The other errors in bubble measurement are not easily evaluated. The curved wall of the graduated cylinder is a lens, magnifying the horizontal diameter of the air bubbles. The magnification was more pronounced when the cylinder was in air than in water, because the refractive index of water is closer to that of the glass than is that of the air. Consequently, bubbles appeared larger than they actually were when the cylinder was in air, and the observed rate of rise appeared correspondingly slow. This is the most obvious explanation for the higher values of the radius of the oil shell calculated from the data obtained with the cylinder in air. The distance of the bubble from the wall also changed the degree of magnification, so even the relative values in a series would not be quite correct if the bubbles deviated in their paths. Likewise bubbles rising through a liquid are not truly spherical.

The timing of the bubbles with a stop watch was precise to about ±0.2 second. The shortest times measured were about 20 seconds; hence the maximum error from this source was 1 percent. An estimate of the average error would be about 0.4 percent. Here again, however, the greatest error is not in the measurement itself. There were convection currents in the oil, as noted from the movements of the emulsion droplets in the oils containing foam inhibitors. With the cylinder immersed, these currents were only rarely observable, but the bubbles themselves must cause some convection. The temperature of the oil changed at the rate of about 0.20° C per hour even with the cylinder immersed, apparently mostly because of absorbed radiation, despite 9 inches of water between the oil column and the light source.

The importance of the relative viscosities of the different oils used is apparent from the equations used in the calculations: the velocity of rise varies inversely as the viscosity, and the viscosity changes roughly 8 percent per degree of temperature change. The viscosities used in the calculations were measured with a MacMichael viscosimeter, and the temperature-viscosity curves plotted. To establish the relative viscosities more precisely, the values were redetermined using an Ostwald-type capillary viscosimeter immersed in a water bath at 25.00° C. The viscosimeter was calibrated against the viscosity of a National Bureau of Standards reference oil. The deviation of viscosities measured in this way was less than 0.5 percent. The results are shown in the following table:

Oil	Viscosity by Ostwald-type viscosimeter			Viscosity used in calculations	
	Time (sec)	Measured (stoke)	Relative	Measured (stoke)	Relative
National Bureau of Standards reference standard oil	251.0	10.06	----	8.40	1.00
Aeroshell 120	224.5	9.00	1.00	8.40	1.00
Aeroshell 120 containing 0.1 percent Dow Corning Fluid Type 200	224.0	8.98	1.00	8.40	1.00
Aeroshell 120 containing 0.075 percent glycerol and 0.025 percent Aerosol OT	234.5	9.40	1.05	8.40	1.00
RPM Aviation 120	271.1	10.87	1.21	10.40	1.24

The difference in relative viscosities as measured and as used in the calculations is seen to be 5 percent maximum. This is not significant in affecting the interpretation given to the data.

The best estimate of the over-all precision of the data is obtained from analysis of the values for the ratio of the squares of the diameters of bubbles, observed and calculated as presented in the tables. Such a discussion appears in a later section.

RESULTS AND DISCUSSION

The data are presented completely in tables I to VII. Tables I, II, III, and IV present the measurements made on oils in a graduated cylinder standing in air, and tables V, VI, and VII present the measurements made with the graduated cylinder immersed in a large water reservoir.

The most significant figures in these tables are contained in the column at the extreme right. This ratio represents the comparison of the squares of the observed bubble diameters with the squares of the calculated bubble diameters, which may also be interpreted as the ratio of the expected to the actual velocity of rise, or the ratio of the outside diameter of a shell of rigid oil carried by the bubble to the diameter of the bubble itself. Provided the absolute values of all constants used are exact and the measurements accurate, this ratio must be unity unless there is some difference between the bubble in actuality and the concept of a smooth sphere moving through a Newtonian liquid. Average values, the average deviation from average, and the number of values (given in parentheses) taken from the tables, for the four oils measured, compare as follows:

COMPARISON OF AVERAGED VALUES OF $\frac{(D_a)^2}{(D_a')^2}$

Oil	Cylinder in air	Cylinder immersed in water
Aeroshell 120	1.40 ± 0.18 (10)	0.879 ± 0.033 (45)
Aeroshell containing 0.075 percent glycerol and 0.025 percent Aerosol OT	2.08 ± 0.23 (16)	-----------------
Aeroshell containing 0.1 percent Dow Corning Fluid Type 200	1.70 ± 0.11 (22)	1.35 ± 0.15 (24)
RPM Aviation 120	1.28 ± 0.16 (18)	1.02 ± 0.07 (17)

The immediately apparent result is that the ratios are different for the four oils. The average deviations from the average values give some idea of the homogeneity of the data from which the averages were obtained. It is assumed that the value for Aeroshell 120 represents unity, on the basis of the very homogeneous data shown in table VI.

The question of whether RPM Aviation 120 shows any anomaly in the rate of rise of its bubbles requires careful analysis to answer. Only the data obtained with the cylinder immersed are homogeneous enough for this purpose. The inversion of the ratios for RPM Aviation 120 and Aeroshell 120 with the cylinder in air is accounted for by the range of variability of each set of data. It is apparent that the degree of anomaly is small; the apparent separation of the ratios for Aeroshell 120 and RPM Aviation 120 is 14 percent, but the total average deviation from average is 10 percent. Furthermore, as pointed out in the preceding section on precision, there is a 3-percent error in relative viscosity, in the direction to bring the ratios closer together. However, a net difference still exists. This is confirmed by the data of table V(b), which have not been used in the previous calculations.

The data of table V(b) indicate that the velocity of the bubbles rising in RPM Aviation became slower and slower as they rose. The ratio over even the first range, from graduation 20 to 30 is greater than that for Aeroshell 120, confirming the conclusion of the preceding paragraph. It will be seen in table V(b) that, up until graduation 50, the ratios of the squared diameters are in the same range as in table V(a), in which all of the bubbles were timed in the region below graduation 50. The two tables may thus be regarded as confirmatory insofar as the data overlap.

The decrease in velocity in the upper part of the bubble path may be due to either of two causes. The first is a wall effect. As the bubbles rise close to a wall, they tend to move closer to the wall, by Bernoulli's theorem. One series of measurements (not reported) on Aeroshell 120 also showed this effect, although not nearly so pronouncedly, which was eliminated by moving the jet slightly farther away from the wall of the cylinder. The reported data on Aeroshell 120, table VI, show this effect completely missing.

The second cause is that the adsorbed material on the bubble, and hence the diameter of the shell moving with the bubble, may increase as the bubble travels. This is a very reasonable supposition, since it has previously been shown that some of the additive material in RPM Aviation may be removed by collecting it on air bubbles rising through a column of the oil, and segregating the froth which the bubbles form. As a bubble collects adsorbed material, the area swept out would increase and more material would be accumulated, at an exponential rate. The very sharp upswing in the ratio of the squared diameters in table V(b) is rational on this supposition. The diameter of the shell of material moving with the bubble apparently may be double the diameter of the air bubble. The argument for the second cause is strengthened by the demonstration of the same effect in table VII, for Aeroshell containing Dow Corning Fluid Type 200.

The result which has been demonstrated qualitatively is that air bubbles rising through these oils which contain various additives accumulate the additives on their surfaces in great effective thickness, thereby impeding their rate of rise through the oil. The order in which the additives accumulate on the surface of air bubbles is glycerol - Aerosol-OT, most; Dow Corning Fluid Type 200, slightly less; and the lubricating additives in RPM Aviation 120, least. This order is tentative, inasmuch as there is a rate of adsorption involved as well as the magnitude. Also, this order is based on the apparent diameter of the shell moving with the air bubble, rather than on either weight or volume of the additive itself.

The phenomenon is of great interest theoretically as regards the structure of liquids. The antifoam additives add a shell to the air bubbles which can have a diameter half again as great as the air bubble itself. This must mean that a gel-like structure, possibly a plastic solid, extends from the air interface far into the oil. The great extent of this structure (great in terms of molecular size) may be largely due to the motion of the bubbles. Similar experiments on the adsorption of solutes, especially colloids, in aqueous solutions show that the concentration adsorbed on the surface of moving bubbles may be from twice to many times the concentration adsorbed on a plane quiet surface at equilibrium (references 2 and 3).

The wholly or partially immobilized liquid may contain chains of oriented molecules of additive extending outward from a primary adsorbed layer on the surface of the bubble, as suggested independently by McBain and Davies (reference 2) and by Hardy (reference 4) in 1927. This may well be supplemented by cybotactic arrangement of the hydrocarbon molecules in the same region. The practical significance of the observations is that the reluctance to separate of finely emulsified air in lubricating oils containing additives, observed in a mock-up system, has been accounted for.

CONCLUDING REMARKS

Bubbles of air rising at room temperature through Aeroshell 120, an undoped lubricating oil, obey Stokes' Law; that is, they rise as though they were spheres of a diameter equal to their apparent diameter, at a rate proportional to the difference in densities of the air and oil and inversely proportional to the viscosity of the oil.

Bubbles of air rising at room temperature through a doped oil, RPM Aviation (not a military aircraft lubricant), rise slightly more slowly than predicted by Stokes' Law. Similarly, bubbles rising through Aeroshell 120 containing either 0.1 percent Dow Corning Fluid Type 200 or 0.075 percent glycerol and 0.025 percent Aerosol OT rise at a rate considerably slower than that predicted by Stokes' Law. As the age of the bubble increases, its rate of rise decreases.

These observations are interpreted as signifying that in the undoped oil (Aeroshell 120) there is no structure in the liquid shell surrounding the bubble. In the oils containing lubricating additives (RPM Aviation 120) or foam inhibitors (Aeroshell with the inhibitors named above), there is a thick shell of material surrounding the bubble which moves with the bubble, impeding its passage through the oil. The maximum thickness of this shell is calculated assuming Stokes' Law, and found to be of the same order as the radius of the air bubble itself.

The shell surrounding air bubbles is evidently due to the additives in the oil, and not due to the oil alone. Adsorption of large magnitude apparently takes place. The motion of the bubbles through the oil probably increases the amount of the adsorption. In the range studied, the shell thickness around large bubbles is about the same proportion of the bubble diameter as that around small bubbles. These observations explain the persistent turbidity due to emulsified air in oils containing certain additives.

Stanford University
Stanford University, Calif., July 26, 1945

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TABLE I.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120

Distance (cm)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder in air								
5.7	25.6	0.223	0.170	28.2	7.00	0.186	286×10^{-4}	1.01
3.8	31.0	.1226	.1512	28.2	7.00	.102	230	1.47
1.9	16.0	.1188	.1420	27.9	7.12	.101	156	1.29
3.8	41.2	.0923	.142	25.5	8.15	.0895	138	1.46
3.8	35.6	.107	.1322	27.8	7.15	.0910	140	1.25
3.8	43.6	.0087	.1322	27.8	7.15	.0741	114	1.53
1.9	62.2	.0305	.0850	28.4	6.90	.0251	38.6	1.87
1.9	59.0	.0322	.0756	27.7	7.20	.0276	42.5	1.34
1.9	80.0	.0238	.0718	27.2	7.40	.0210	32.4	1.60
1.9	110.0	.0173	.0548	27.0	7.47	.0154	23.8	1.26
								Av. 1.40

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TABLE II.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120 CONTAINING

0.075 PERCENT GLYCEROL AND 0.025 PERCENT AEROSOL OT

Distance (cm)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder in air								
3.8	18.7	0.203	0.232	26.1	7.86	0.190	293×10^{-4}	1.84
3.8	23.2	.164	.189	27.6	7.23	.141	218	1.64
3.8	38.0	.100	.185	26.0	7.90	.0942	145	2.36
3.8	34.2	.111	.161	27.6	7.23	.0955	147	1.77
1.9	31.0	.0613	.142	27.5	7.27	.0535	82.5	2.45
3.8	68.0	.0559	.132	27.1	7.43	.0494	76.0	2.30
3.8	71.1	.0534	.127	26.3	7.77	.0494	76.0	2.13
3.8	72.3	.0526	.127	27.0	7.47	.0469	72.3	2.24
1.9	27.2	.0698	.123	27.0	7.47	.0621	95.7	1.59
1.9	51.3	.0371	.117	25.9	7.95	.0351	54.0	2.54
1.9	40.2	.0472	.113	27.8	7.15	.0402	62.0	2.06
3.8	127.0	.0299	.100	26.3	7.77	.0277	42.6	2.34
3.8	133.2	.0285	.0906	26.5	7.68	.0260	40.0	2.05
3.8	133.8	.0284	.0850	26.7	7.60	.0257	39.8	1.81
1.9	114.0	.0167	.0700	26.0	7.90	.0157	24.2	2.02
1.9	123.0	.0154	.0681	25.9	7.95	.0146	22.5	2.06
								Av. 2.08

TABLE III.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120 CONTAINING 0.1 PERCENT DOW CORNING FLUID TYPE 200

Distance (cm)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder in air								
3.8	34.3	0.1140	0.1512	26.9	7.50	0.102	157×10^{-4}	1.46
3.8	43.2	.0880	.1474	27.3	7.35	.0770	119	1.83
3.8	45.3	.0839	.1417	26.9	7.50	.0749	105	1.91
3.8	47.4	.0802	.1323	26.9	7.50	.0716	110	1.60
5.7	71.4	.0800	.1322	27.2	7.40	.0705	109	1.60
3.8	42.8	.888	.1322	29.7	6.50	.0686	106	1.65
3.8	55.6	.0683	.123	26.9	7.50	.0610	94.2	1.61
3.8	58.6	.0648	.1228	26.9	7.50	.0579	88.0	1.72
5.7	83.6	.0682	.1210	26.9	7.50	.0609	94.0	1.57
3.8	62.4	.0609	.1171	26.7	7.60	.0544	83.7	1.65
3.8	68.6	.0554	.1133	26.9	7.50	.0495	76.3	1.69
3.8	64.0	.0594	.1133	26.9	7.50	.0530	81.6	1.57
3.8	74.5	.0510	.1114	26.9	7.50	.0455	70.0	1.77
3.8	81.7	.0465	.1020	27.0	7.47	.0414	63.7	1.63
3.8	90.0	.0422	.0983	26.8	7.55	.0377	58.0	1.67
3.8	93.0	.0409	.0945	26.9	7.50	.0365	56.3	1.58
3.8	95.4	.0398	.0906	27.0	7.47	.0354	54.5	1.50
3.8	125.0	.0304	.0813	28.3	6.97	.0252	38.8	1.70
1.9	79.0	.0240	.0700	29.3	6.63	.0189	29.1	1.68
1.9	178.0	.0107	.0529	26.9	7.50	.00955	14.7	1.90
1.9	254.0	.0075	.0454	26.6	7.65	.0067	10.3	2.00
.19	27.3	.0069	.0454	26.6	7.65	.00616	9.5	2.16
								Av. 1.70

TABLE IV.- RISE OF AIR BUBBLES THROUGH RPM AVIATION 120

Distance (cm)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder in air								
3.8	22.3	0.1705	0.186	25.4	10.20	0.1670	319×10^{-4}	1.08
3.8	33.9	.1121	.1548	25.4	10.20	.1100	210	1.14
3.8	38.2	.0993	.1454	25.5	10.15	.0970	185	1.14
3.8	40.0	.0950	.1398	26.7	9.50	.0868	165.6	1.18
3.8	39.0	.0975	.1378	25.2	10.30	.0965	184	1.03
3.8	56.0	.0679	.1228	25.5	10.15	.0662	126.3	1.19
1.9	35.3	.0539	.1096	26.7	9.50	.0493	94.0	1.28
1.9	48.0	.0396	.1039	25.6	10.10	.0384	73.3	1.42
3.8	69.0	.0551	.1020	25.2	10.30	.0546	104.3	1.00
3.8	100.0	.0380	.0906	25.2	10.30	.0376	71.7	1.14
1.9	58.9	.0325	.0906	25.8	10.00	.0313	59.8	1.37
3.8	140.5	.0270	.0812	25.3	10.25	.0266	50.7	1.30
3.8	135.8	.0280	.0813	25.6	10.10	.0272	51.9	1.27
3.8	218.0	.0174	.0642	25.2	10.30	.0172	32.8	1.26
.19	23.3	.00804	.0491	25.1	10.35	.00800	15.3	1.58
1.9	232.0	.00819	.0454	26.1	9.80	.00772	14.7	1.40
1.9	290.0	.00655	.0378	26.5	9.60	.00605	11.5	1.24
.19	147.0	.00128	.0227	25.0	10.40	.00128	2.4	2.1
								Av. 1.28

TABLE V.- RISE OF AIR BUBBLES THROUGH RPM AVIATION 120

(a) Velocity of rise near center of cylinder

[Each group of data represents a single bubble, observed over different intervals. The last bubble was timed in its movement across the field of the telescope.]

Distance (cm)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder immersed in water								
3.8	62.1	0.0612	0.1082	24.4	10.75	0.0633	121×10^{-4}	0.967
3.8	59.6	.0637	.1082	24.3	10.80	.0662	126.5	.925
3.8	67.3	.0565	.1063	24.4	10.75	.0585	111.8	1.01
3.8	71.6	.0530	.1008	24.3	10.80	.0550	105.0	.972
1.9	33.1	.0574	.1008	24.5	10.70	.0591	113.0	.904
3.8	112.4	.0338	.0816	24.3	10.80	.0351	67.0	1.00
7.6	267.0	.0285	.0798	24.2	10.85	.0298	56.9	1.12
1.9	70.4	.0270	.0779	24.4	10.75	.0279	53.3	1.15
1.9	66.4	.0286	.0760	24.4	10.75	.0296	56.5	1.03
5.7	196.0	.0291	.0741	24.4	10.75	.0301	57.5	.956
3.8	136.5	.0278	.0741	24.3	10.80	.0288	55.0	1.00
3.8	139.0	.0273	.0722	24.2	10.85	.0285	54.5	.954
3.8	150.0	.0253	.0722	24.3	10.80	.0263	50.2	1.03
3.8	155.2	.0245	.0703	24.3	10.80	.0254	48.5	1.02
5.7	259.0	.0220	.0703	24.4	10.75	.0228	43.5	1.13
3.8	172.0	.0221	.0665	24.4	10.75	.0229	43.7	1.01
1.9	195.0	.00975	.0494	24.4	10.95	.0101	19.3	1.26
								Av. 1.02

TABLE V.- RISE OF AIR BUBBLES THROUGH RPM AVIATION 120 - Concluded

(b) Change in velocity of rise from bottom to top of cylinder

[Each group of data represents a single bubble, observed over different intervals. The last bubble was timed in its movement across the field of the telescope.]

Interval (graduations) (1)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder immersed in water								
20 to 30	21.8	0.0872	------	23.9	11.05	0.0925	176.4×10^{-4}	0.921
30 to 40	23.5	.0808	0.1273	23.9	11.05	.0857	163.5	.992
40 to 50	25.4	.0749	.1253	23.9	11.05	.0795	151.6	1.04
50 to 60	29.0	.0655	.1234	23.9	11.05	.0695	132.5	1.15
60 to 70	33.0	.0575	.1216	23.9	11.05	.0610	116.3	1.27
70 to 80	37.5	.0506	.1234	23.9	11.05	.0537	102.6	1.48
20 to 30	25.8	.0736	------	23.4	11.35	.0806	154	.936
30 to 40	27.8	.0684	------	23.4	11.35	.0749	143	1.01
40 to 50	31.0	.0614	------	23.4	11.35	.0672	128	1.13
50 to 60	35.5	.0535	.1198	23.4	11.35	.0584	111	1.30
60 to 70	41.6	.0456	.1160	23.4	11.35	.0498	95.0	1.41
70 to 80	45.4	.0419	.1140	23.4	11.35	.0457	87.2	1.49
20 to 30	41.6	.0456	------	23.3	11.45	.0502	95.8	.943
30 to 40	46.0	.0413	------	23.3	11.45	.0455	86.9	1.04
40 to 50	54.6	.0342	.0950	23.3	11.45	.0377	72.0	1.25
50 to 60	59.2	.0321	------	23.3	11.45	.0354	67.5	1.23
60 to 70	74.6	.0255	.0912	23.3	11.45	.0280	53.5	1.56
70 to 80	82.7	.0230	------	23.3	11.45	.0253	48.3	1.73
20 to 30	59.8	.0318	------	23.7	11.17	.0342	65.3	1.03
30 to 40	67.0	.0284	.0817	23.7	11.17	.0305	58.2	1.15
40 to 50	75.6	.0252	.0799	23.7	11.17	.0270	51.5	1.24
50 to 60	89.5	.0212	.0779	23.7	11.17	.0228	43.5	1.40
60 to 70	112.0	.0170	.0760	23.7	11.17	.0183	34.9	1.66
70 to 80	121.1	.0157	.0760	23.7	11.17	.0169	32.2	1.79
20 to 30	78.4	.0242	------	23.5	11.30	.0263	50.2	1.04
30 to 40	89.1	.0214	.0722	23.5	11.30	.0232	44.3	1.18
40 to 50	100.4	.0189	.0722	23.5	11.30	.0205	39.2	1.33
50 to 60	120.9	.0157	.0703	23.5	11.30	.0171	32.6	1.51
60 to 70	155.6	.0122	.0685	23.5	11.30	.0133	25.4	1.85
70 to 80	169.2	.0112	.0665	23.5	11.30	.0121	23.1	1.91
0.19 at 37	16.2	.0117	.0551	23.9	11.05	.0124	23.6	1.29
.19 at 44	16.9	.0112	.0532	23.9	11.05	.0119	22.7	1.25
.19 at 50	18.7	.0102	.0532	23.9	11.05	.0108	20.6	1.38
.19 at 60	24.9	.00763	.0513	23.9	11.05	.00810	15.4	1.71
.19 at 70	33.2	.00572	.0494	23.9	11.05	.00608	11.6	2.02
.19 at 80	39.7	.00479	.0475	23.9	11.05	.00510	9.7	2.33

[1] Interval of 10, that is, 10 to 20, corresponds to 1.9 centimeters.

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TABLE VI.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120

[Each group of data represents a single bubble, observed over different intervals.]

Interval (graduations) (a)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder immersed in water								
20 to 30	18.4	0.1032	------	24.1	8.87	0.1090	168×10^{-4}	0.858
30 to 40	18.4	.1032	------	24.1	8.87	.1090	168	.858
40 to 60	36.3	.1046	.1198	24.1	8.87	.1104	170	.846
60 to 70	19.2	.0990	------	24.1	8.87	.1046	161	.869
70 to 80	19.0	.1000	.1179	24.1	8.87	.1057	163	.853
50 to 60	19.6	.0969	.1140	24.7	8.55	.0985	151.8	.856
20 to 30	21.0	.0905	------	24.7	8.55	.0920	141.8	.917
30 to 50	40.0	.0950	.1140	24.7	8.55	.0966	149.0	.872
50 to 70	38.6	.0986	.1102	24.7	8.55	.1003	154.5	.792
70 to 80	20.8	.0914	------	24.7	8.55	.0930	143.2	.850
30 to 40	30.2	.0629	.0912	24.7	8.55	.0640	98.6	.844
40 to 50	30.5	.0623	------	24.7	8.55	.0634	97.6	.853
50 to 60	30.4	.0625	.0912	24.7	8.55	.0636	98.0	.850
60 to 70	31.8	.0597	.0912	24.7	8.55	.0608	93.6	.889
20 to 30	25.2	.0754	------	24.7	8.55	.0766	118	[b].594
30 to 70	99.7	.0762	.0836	24.7	8.55	.0796	119.6	[b].586
70 to 80	29.0	.0655	.0950	24.7	8.55	.0666	102.6	.880
20 to 30	37.8	.0503	------	22.1	9.95	.0595	91.6	.871
30 to 40	37.7	.0504	------	22.1	9.95	.0596	91.9	.869
50 to 60	----	------	.0893	22.1	9.95	------	---------	-----
60 to 70	40.6	.0468	------	22.1	9.95	.0554	85.5	.893
70 to 80	41.0	.0464	.0874	22.1	9.95	.0549	84.6	.902

[a] Interval of 10, that is, 10 to 20, corresponds to 1.90 centimeters.

[b] These figures not used in computing average.

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TABLE VI.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120 - Concluded

[Each group of data represents a single bubble, observed over different intervals.]

Interval (graduations) (a)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder immersed in water								
20 to 30	45.0	0.0422	0.0760	24.1	8.87	0.0450	69.4×10^{-4}	0.833
40 to 50	46.2	.0411	.0760	24.1	8.87	.0439	67.5	.855
50 to 60	47.3	.0402	.0760	24.1	8.87	.0425	65.5	.882
60 to 70	48.6	.0390	.0741	24.1	8.87	.0412	63.5	.866
70 to 80	50.4	.0377	.0722	24.1	8.87	.0398	61.4	.852
20 to 30	64.0	.0297	------	24.1	8.87	.0314	48.4	.895
30 to 40	65.7	.0289	.0665	24.1	8.87	.0305	47.0	.921
40 to 50	66.2	.0287	.0646	24.1	8.87	.0303	46.6	.896
50 to 60	67.1	.0283	.0646	24.1	8.87	.0299	46.1	.907
60 to 70	70.4	.0270	.0626	24.1	8.87	.0285	44.0	.894
70 to 80	71.1	.0267	.0589	24.2	8.81	.0282	43.5	.796
30 to 40	76.8	.0248	.0589	24.0	8.95	.0264	40.6	.852
40 to 50	79.0	.0240	.0589	24.0	8.95	.0256	42.1	.878
50 to 60	80.8	.0235	.0570	24.0	8.95	.0250	41.1	.840
60 to 70	85.0	.0224	.0551	24.0	8.95	.0239	39.3	.826
70 to 80	86.5	.0220	.0551	24.0	8.95	.0234	36.0	.845
20 to 30	90.8	.0210	------	23.7	9.10	.0228	35.2	.750
30 to 40	93.7	.0203	------	23.7	9.10	.0220	33.9	.779
60 to 70	104.0	.0183	.0514	23.7	9.10	.0198	30.5	.865
70 to 80	108.4	.0175	------	23.7	9.10	.0190	29.3	.900
20 to 30	100.4	.0189	------	24.2	8.80	.0200	30.8	.857
30 to 40	104.4	.0182	.0514	24.2	8.80	.0192	29.6	.892
40 to 50	106.0	.0179	.0514	24.2	8.80	.0189	29.1	.909
50 to 60	109.8	.0173	.0475	24.2	8.80	.0183	28.2	.801
60 to 70	119.4	.0159	.0475	24.2	8.80	.0168	25.9	.874
70 to 80	123.0	.0154	.0456	24.2	8.80	.0163	25.2	.825
								Av. 0.879

[a]Interval of 10, that is, 10 to 20, corresponds to 1.90 centimeters.

TABLE VII.- RISE OF AIR BUBBLES THROUGH AEROSHELL 120 CONTAINING

0.1 PERCENT DOW CORNING FLUID TYPE 200

[Each group of data represents a single bubble, observed over different intervals.]

Interval (graduations) (1)	Time (sec)	Velocity, V	Observed diameter, D_a	Temperature (°C)	Viscosity, ν	Velocity at 25° C	Calculated diameter squared, $(D_a')^2$	Ratio of squared diameters, $\frac{(D_a)^2}{(D_a')^2}$
Cylinder immersed in water								
30 to 40	24.6	0.0772	------	25.1	8.37	0.0770	118.8 × 10^{-4}	1.29
40 to 50	24.7	.0769	0.1235	25.1	8.37	.0766	118.2	1.29
50 to 60	25.0	.0760	------	25.1	8.37	.0758	116.9	1.28
60 to 70	26.3	.0722	------	25.1	8.37	.0719	111.0	1.33
70 to 80	30.0	.0634	.1197	25.1	8.37	.0631	97.4	1.47
50 to 60	59.1	.0321	.0950	25.2	8.30	.0317	48.8	1.85
60 to 70	60.8	.0312	.0950	25.2	8.30	.0308	47.5	1.90
70 to 80	60.7	.0312	.0950	25.2	8.30	.0308	47.5	1.90
30 to 40	40.4	.0470	------	25.3	8.25	.0461	71.2	1.27
40 to 50	39.4	.0482	.0950	25.3	8.25	.0474	73.0	1.24
50 to 60	40.2	.0472	.0912	25.3	8.25	.0464	71.5	1.16
60 to 70	42.4	.0449	.0912	25.3	8.25	.0441	68.0	1.22
70 to 80	45.0	.0422	.0912	25.3	8.25	.0415	64.0	1.30
30 to 40	62.0	.0306	------	25.1	8.35	.0305	47.0	1.11
40 to 50	66.2	.0287	.0722	25.1	8.35	.0286	44.1	1.19
50 to 60	68.2	.0278	.0722	25.1	8.35	.0277	47.7	1.10
60 to 70	73.1	.0260	.0722	25.1	8.35	.0259	40.0	1.31
70 to 80	77.4	.0246	.0722	25.1	8.35	.0245	27.8	1.38
30 to 40	70.8	.0268	------	25.0	8.40	.0268	41.4	1.19
40 to 50	73.4	.0259	------	25.0	8.40	.0259	40.0	1.23
50 to 60	75.6	.0251	.0703	25.0	8.40	.0251	38.7	1.27
60 to 70	79.3	.0240	.0703	25.0	8.40	.0240	37.0	1.33
70 to 80	81.0	.0234	.0703	25.0	8.40	.0234	36.1	1.37
70 to 80	98.0	.0194	.0627	25.3	8.25	.0191	29.5	1.34
								Av. 1.35

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[1] Interval of 10, that is, 10 to 20, corresponds to 1.90 centimeters.

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