# A Determination of the Terminal Velocity and Drag of Small Water Drops by Means of a Wind Tunnel

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ABSTRACT

Measurements of the drag on small water drops falling in water-saturated air at terminal velocity were carried out in a wind tunnel for Reynolds numbers R between 0.2 and 200. The fractional deviation $(D/D_0)-1$ of the actual drag $D$ from the Stokes drag $D_0$ was determined as a function of R and empirical formulae for $(D/D_0)-1$ were derived for the three ranges $0.2\leq R\leq 2$, $2\leq R\leq 21$ and $21\leq R\leq 200$. From these relations drag coefficients were computed and the terminal velocity of water drops of radii between 10 and 475 $\mu$ calculated for drops falling in water-saturated air and at pressure levels of 400, 500, 700 and 1013 mb, where the temperature was assumed to be −16, −8, 14 and 20C, respectively.

It is shown, for $0.2\leq R\leq 200$, that the values derived for the drag on water drops are in good agreement with those for the drag on solid spheres experimentally determined by Pruppacher and Steinberger, and with those for the drag on solid spheres theoretically computed by Rimon. It is pointed out that there is a strong scatter among the values for the terminal velocity of water drops given in literature. Out data agreed quite closely with those of Gunn and Kinzer.

## 1. Introduction

Frequently there is a need in meteorological studies to have available for computation a knowledge of the hydrodynamic drag and terminal velocity of water drops for given atmospheric conditions. A large number of investigators (Lenard, 1904; Schmidt, 1909; Liznar, 1914; Flower, 1928; Laws, 1941; Gunn and Kinzer, 1949; Imai, 1950; Kumai and Itagaki, 1954) have reported on their determination of the terminal velocity of falling rain and water drops. A summary of the results of these investigations is presented in Fig. 1. It is seen from this figure that the results of individual investigators differ significantly. A close scrutiny of the conditions under which the different investigations were carried out led us to believe that the reported results probably were biased due to the fact that the falling drops either were evaporating or had not reached terminal velocity. In addition, most of the experimental techniques used to determine the fall velocity and the size of the drops were inadequate and too crude to give accurate results. The results reported suffer further from the fact that most measurements were made with water drops of radii $>200\ \mu$, with the exception of Gunn and Kinzer who made a few measurements of the terminal velocity of water drops of radii between 39 and 200 $\mu$. Even though the study of Gunn and Kinzer so far has been regarded as the most complete and has been widely quoted in the literature, we feel that it is subject to some question since the drops were allowed to fall in an environment of air of only 50% relative humidity. The fact that Gunn and Kinzer's data are fairly well supported by those of Laws and Imai is not necessarily in favor of Gunn and Kinzer's results since the measurements of Laws were rather crude and the accuracy of the theoretical calculations of Imai was limited by several simplifying approximations.

Langmuir (1948), Mason (1957), McDonald (1960) and Cornford (1965) suggested a method to determine the terminal velocity $V_\infty$ of water drops from a relation between the drag coefficient $C_D$ and $C_D R^2$. This method depends on the knowledge of $C_D$ as a function of R. Langmuir and Mason used the relationship between $C_D$ and R given theoretically by Goldstein (1929), McDonald used that given by Schlichting (1955), and Cornford used the values for $C_D$ given by Gunn and Kinzer. However, it has been shown recently by Pruppacher and Steinberger (1968) that the experimental and theoretical relationships between $C_D$ and R generally available in literature are in considerable error.

The reasons cited above and the fact that new experimental tools and techniques have become available since the last investigation of $V_\infty$ of water drops motivated us to carry out new experiments to determine the terminal velocity and drag of small water drops under more accurately controlled conditions.

## 2. Experimental setup

The present investigations were carried out by means of a wind tunnel constructed at UCLA for cloud physics research. The main features of this tunnel (henceforth called cloud tunnel) were discussed by Pruppacher and

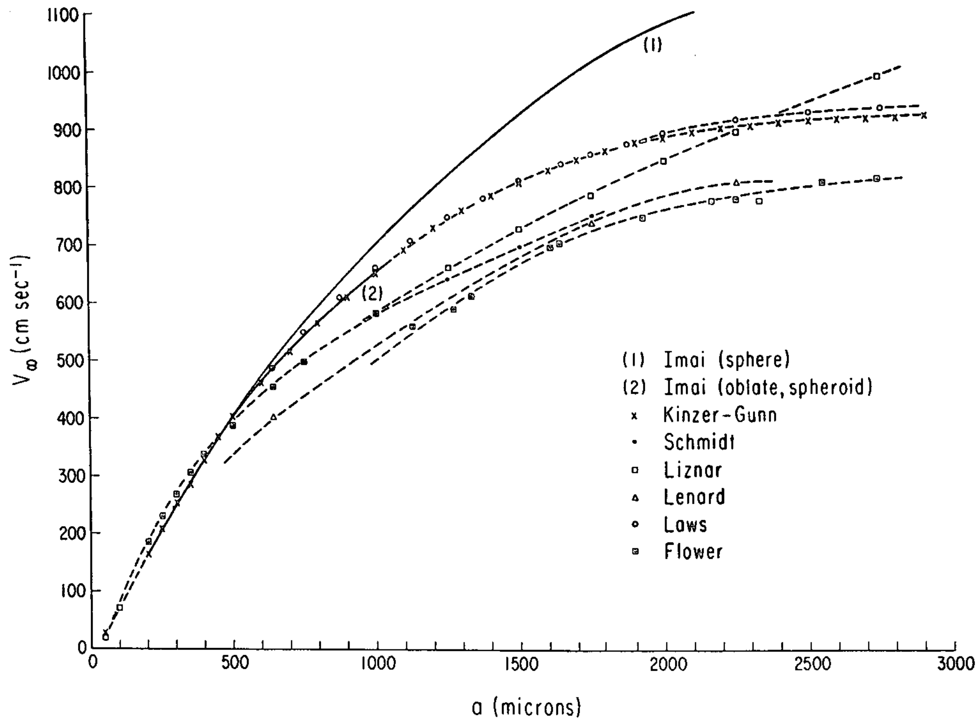


FIG. 1. Terminal velocity of water and rain drops as a function of their equivalent spherical radius $a$. (From results cited in the literature.)

Neiburger (1968). Briefly, the cloud tunnel, fabricated out of aluminum and stainless steel, consists of a horizontal air conditioning system and a vertical flow control system. The air is propelled through these two systems by means of a vacuum pump. The air conditioning system allows the relative humidity of the tunnel air in the observation section to be varied in a controlled manner between 1 and 100%, and the temperature between room temperature and −40C. The flow control system smooths the flow and controls the air speed. The smoothing is achieved by means of a large stilling chamber, honeycomb, screens and a contraction section. The air speed in the observation section is varied in a controlled manner by varying the position of a paraboloidal plug in the constriction of the tunnel just upstream of the vacuum pump. The constriction was designed so that the air speed in it is sonic for all air speeds between 1 cm sec$^{-1}$ and 8 m sec$^{-1}$ in the observation section. This sonic flow control valve prevents disturbances in the flow created by the pump from propagating upstream, and allows rapid and accurate velocity control in the observation section which is just downstream of the contraction section. Under the conditions that the air speed is sonic in the valve, the Mach number M at any position upstream in the tunnel (in particular in the observation section) is given by the relation

$$A/A^* = (1/\mathrm{M})\{(2/\kappa+1)[1+\mathrm{M}^2(\kappa-1)/2]\}^{(\kappa+1)/2(\kappa-1)}, \quad (1)$$

where $\mathrm{M}=U/C$, $U$ being the free stream velocity of the air in the observation section and $C$ the speed of sound, $A$ is the cross-sectional area of the observation section, $A^*$ the cross-sectional area of the sonic value, and $\kappa=C_p/C_v$. Since the area ratio $A/A^*$ is not exactly known for all positions of the control paraboloid in the sonic valve, $U$ had to be calibrated. This was done in a preliminary manner (Pruppacher and Neibruger, 1968) by means of a method developed by Roshko (1953, 1954a,b). However, a careful analysis showed that the calibration formulae developed by Roshko and later by Tritton (1959) were not exact enough. The final calibration of the velocity in the cloud tunnel was carried out by the Roshko method with the formula given by Berger (1964). Small metal rods of diameters between 1/64 and 7/64 inches were held rigidly in the tunnel perpendicular to the tunnel air stream. The probe (5 $\mu$ diameter platinum wire on a 3 mm diameter rectangular probe support) of a hot wire anemometer unit (DISA-S & B Inc., Model 55D01) connected to an auxiliary unit (DISA-S & B, Model 55D25) for amplification and filtering noise was held in the wake of the rod. The shedding frequency of the vortices from the rod was determined by means of the Lissajou figure method. The signal of the hot wire anemometer and the signal of a Hewlett-Packard oscillator (Model 241A) were fed into an oscilloscope (Tektronix, Model 515A) on perpendicular coordinates. The frequency necessary to produce a Lissajou ellipse for a given signal of the hot wire anemometer was recorded by an electronic counter (Hewlett-Packard, Model 523 DR). From a knowledge of the shedding frequency $n$ of the vortices from the rod of diameter $d$, the air speed $U$ in the tunnel was computed from the empirical formula given by Berger, i.e.,

$$(nd/U)=1.625\times10^{-4}\mathrm{R}^2+0.164\mathrm{R}-2.55,\quad 50\leq\mathrm{R}\leq90. \qquad (2)$$

The results obtained from this method of calibration were checked by the familiar pressure method. For this purpose a Prandtl type pitot-static tube of $\frac{1}{8}$ inch diameter (United Sensor & Control Corporation, Model PCC-12 KL) was exposed to the tunnel air stream and the pressure differential measured by means of a high precision micromanometer (Hero, West Germany). The velocity was then computed from the relation

$$U=(2\Delta p/\rho)^{\frac{1}{2}}. \qquad (3)$$

For the case $U>350$ cm sec$^{-1}$ the velocity calibration obtained by the two methods agreed within 1 cm sec$^{-1}$. For $U<350$ cm sec$^{-1}$ agreement within 1 cm sec$^{-1}$ was obtained after the low Reynolds number correction given by Ower (1949) was applied. The velocity profile in the tunnel was determined at several locations up and downstream of the observation section and was found to be essentially flat. This is illustrated for one particular setting of the sonic valve in Fig. 2. Similar velocity profiles were obtained for other valve settings. Extensive tests showed that water drops of radius between 10 and 450 $\mu$ could be stably suspended by the tunnel air in the test section under all temperature and humidity conditions of interest, and for any desired length of time. A particular drop would stay close to the tunnel axis and within a few millimeters of a desired location in the tunnel.

In a particular experiment the relative humidity of the air in the observation section was raised to 100% by adjusting the humidifier in the air conditioning section and kept constant by monitoring the dew-point temperature to $\pm0.5$C with a dew-point hygrometer (Cambridge Systems, Model 992-C1). The temperature of the tunnel air was monitored to $+0.2$C at various locations in the observation section by means of copper-constantan thermocouples calibrated against a National Bureau of Standards resistance thermometer, and connected to a 12-point readout potentiometer (Leeds-Northrup, Model Speedomax W, Azar, Flexelect A). A water drop of desired size was injected into the air stream by means of a vibrating hypodermic needle. By adjusting the velocity of the air stream the drop was suspended at a location on the tunnel axis where the velocity was calibrated. The size of a drop floating in the tunnel air was determined by means of a photographic method. The drops were photographed from a distance of about 100 mm by a modified Nikon camera fitted with a 90-mm Makro-Kilar lense, extension tubes and a specially constructed occular. The shutter speed of the camera was synchronized to a Strobotac (General Radio, Model 1531-A) used to illuminate the background of the drop. Kodak Linograph 35 mm Shellburst film (SGE 421) was used to obtain a superior image of the drop. During the time the pictures were taken the drop was neither moving upstream nor downstream in the tunnel so that $V_\infty=U$, where $V_\infty$ is the terminal velocity of the drop and $U$ the air speed in the tunnel.

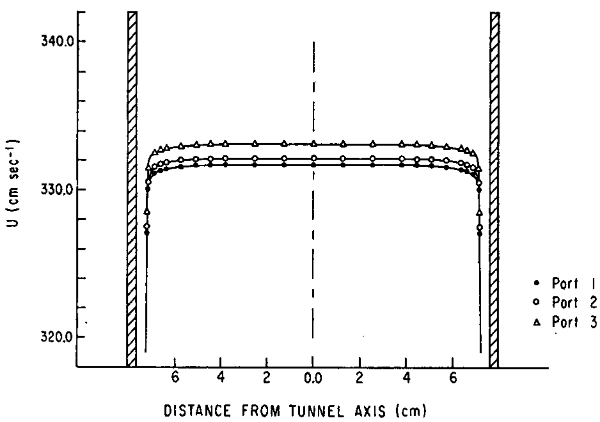


FIG. 2. Velocity profile in UCLA cloud tunnel. Separation between ports 1 and 2 is 1.3 cm and between ports 2 and 3 is 2.9 cm.

## 3. Procedure of data analysis

The photographs of the floating drops were analyzed by means of a microscope. The radius $a$ of a drop was determined by comparison with a calibrated glass scale and the terminal velocity $V_\infty$ determined from the air speed necessary to suspend the drop. From the knowledge of $V_\infty$ and radius $a$, the drag $D$ of the drop nondimensionalized by the Stokes drag $D_s$ was computed from considerations outlined below.

The drag coefficient $C_D$ of a sphere of radius $a$ moving in a viscous medium of density $\rho_m$ and dynamic viscosity $\eta$ is defined by

$$D=C_D(\rho_m/2)(V_\infty^2a^2\pi). \qquad (4)$$

Introducing into (4) the Reynolds number R, defined by

$$\mathrm{R}=2aV_\infty\rho_m/\eta, \qquad (5)$$

we obtain for the drag

$$D=(C_D\mathrm{R}/24)(6\pi a\eta V_\infty). \qquad (6)$$

Further, it can be shown that the solution of the equation of motion for very small values of R (Stokes flow) leads to

$$D_s=6\pi a\eta V_\infty. \qquad (7)$$

Since at terminal velocity the drag on the sphere is balanced by the net gravitational force on it, we have

$$D=(4/3)\pi a^3(\rho_s-\rho_m)g, \qquad (8)$$

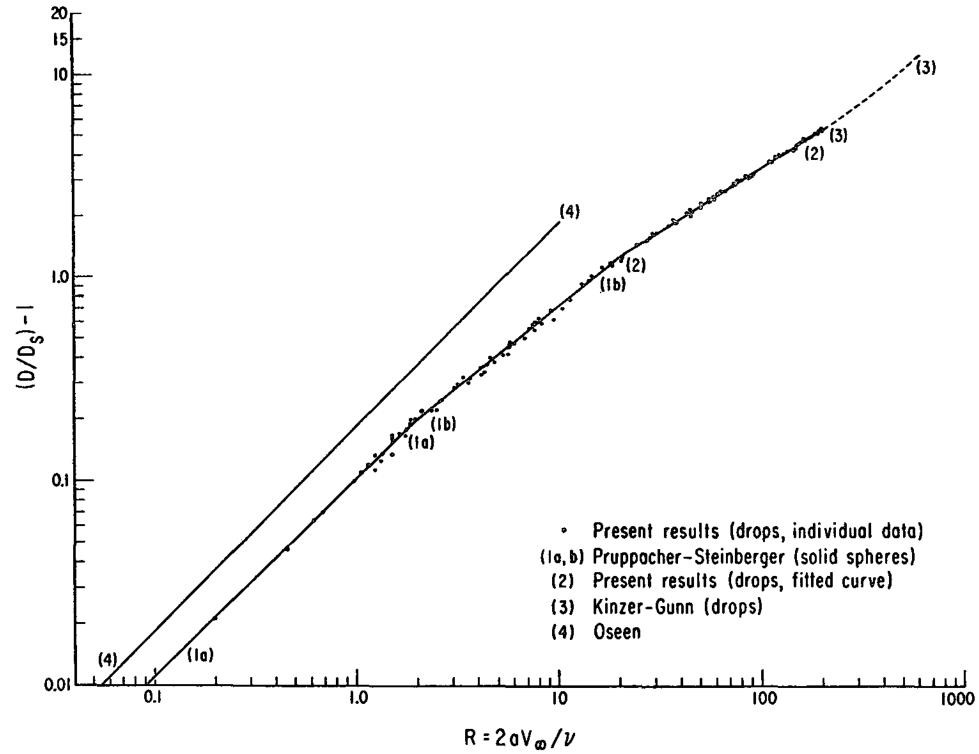


FIG. 3. Variation of the normalized drag of water drops with Reynolds number, based on 173 observations.

where $\rho_s$ is the density of the sphere and $g$ the gravitational acceleration. Combining (8) and (6) we obtain

$$V_\infty = (16/3)[g(\rho_s - \rho_m)/\eta](a^2/C_D\mathrm{R}). \quad (9)$$

For Stokes flow, for which $(C_D\mathrm{R}/24)=1$, (9) reduces to the familiar equation

$$V_s = (2/9)[g(\rho_s - \rho_m)/\eta]a^2. \quad (10)$$

From (7) and (8) we obtain for the nondimensionalized drag

$$(D/D_s) = (2/9)a^2 g(\rho_s - \rho_m)/(\eta V_\infty) = (V_s/V_\infty). \quad (11)$$

From (6) and (7) we find

$$C_D = (24/\mathrm{R})(D/D_s), \quad (12)$$

and therefore from a combination of (11) and (12),

$$C_D = (8/3)[(\rho_s/\rho_m) - 1](ga/V_\infty^2). \quad (13)$$

Eliminating $V_\infty$ from (11) by introducing the Reynolds number and arranging terms, we obtain for the radius of the sphere

$$a^3 = (9/4)[\eta^2/\rho_m(\rho_s - \rho_m)g]\mathrm{R}(D/D_s). \quad (14)$$

From the experimental values of $V_\infty$ and $a$, $D/D_s$ was computed using Eq. (11), and, following the suggestion of Maxworthy (1965), values for the quantity $(D/D_s)-1$ were calculated. An analysis of $(D/D_s)-1$ plotted vs R on a log-log scale showed that our data fitted a straight line in each of three successive Reynolds number intervals. Therefore, in each of these intervals the quantities $\log[(D/D_s)-1]$ as a function of logR were fitted by a straight line with the least-square method using a 360/75 IBM electronic computer. From these empirical relations for $D/D_s$ vs R the drag coefficient $C_D$ was computed as a function of R from (12). The radius $a$ of a spherical water drop falling in water-saturated air at various pressures and temperatures was computed as a function of R from (14). The terminal velocity $V_\infty$ of these drops was then calculated as a function of $a$ from[1]

$$V_\infty = \mathrm{R}\eta/(2\rho_m a). \quad (15)$$

## 4. Results

The variation of $(D/D_s)-1$ with R is plotted in Fig. 3 which shows that our data on a log-log scale fit a straight line in each of three Reynolds number intervals. The least-square method gave the following empirical formulae at the 95% confidence level:

$$(D/D_s) = 1 + (0.10 \pm 0.02)\mathrm{R}^{(0.99\pm0.05)}, \quad 0.2 \le \mathrm{R} \le 2, \quad (16)$$

$$(D/D_s) = 1 + (0.11 \pm 0.01)\mathrm{R}^{(0.81\pm0.03)}, \quad 2 \le \mathrm{R} \le 21, \quad (17)$$

$$(D/D_s) = 1 + (0.189 \pm 0.006)\mathrm{R}^{(0.632\pm0.007)}, \quad 21 \le \mathrm{R} \le 200. \quad (18)$$

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[1] Since $0.0003 \le (2a/\text{tunnel diameter}) \le 0.006$, it was assumed that wall effects were negligible.

A comparison between the present results and those obtained by Pruppacher and Steinberger (1968) for solid spheres falling in oil shows that the two results agree within the experimental error. Because of this agreement and the fact that the results of Pruppacher and Steinberger were more accurate and based on a larger number of data than the present results, we felt justified in using the empirical formulae of Pruppacher and Steinberger in the interval $0.2 \leq R \leq 21$; thus,

$$(D/D_s) = 1 + 0.102R^{0.955}, \quad 0.2 \leq R \leq 2, \tag{19}$$

$$(D/D_s) = 1 + 0.115R^{0.802}, \quad 2 \leq R \leq 21. \tag{20}$$

In the interval $21 \leq R \leq 200$, Eq. (18) was used.

The values for $C_D$ computed from these relations were plotted as a function of R in Fig. 4, where our results are compared with those derived theoretically by Stokes (1845), Oseen (1927), Carrier (1953), Jenson (1959) and Rimon (1967), and with the results experimentally derived by Gunn and Kinzer (1949). The drag coefficient of Stokes' theory is given by

$$C_D = 24/R, \tag{21}$$

the drag coefficient of Oseen's theory by

$$C_D = (24/R)[1 + (3/16)R], \tag{22}$$

and the drag coefficient of Carrier's semiempirical theory by

$$C_D = (24/R)[1 + k_C(3/16)R], \tag{23}$$

where $k_C = 0.43$. It is seen from Fig. 4 that our values agree well with the values given by Gunn and Kinzer. For $R \leq 200$ our results also agree well with those derived by Rimon, and for $R < 10$ with those derived by Carrier. The results derived by Jenson lie everywhere significantly above our experimental results. At $R > 200$ the drag on drops becomes increasingly larger than the drag on solid spheres. This is seen from a comparison between the results of Gunn and Kinzer and those of Rimon.

Following a suggestion of Battan (1964), the variation of $V_\infty$ with $a$ for drops falling in water saturated air at 400, 500, 700 and 1013 mb was determined numerically. The results of this calculation are displayed in Fig. 5, where our results are compared with the Stokes terminal velocities obtained from (10) and with the results of Gunn and Kinzer. It is seen that the terminal velocities given by Gunn and Kinzer are slightly but consistently higher than ours. This is particularly true for the very small drops.

## 5. Discussion and conclusions

It has been shown, for a given Reynolds number, that the drag coefficient, the size, and terminal velocity of drops falling in air of different conditions can readily be calculated by means of the empirical formulae (18), (19) and (20) for the normalized drag $D/D_s$.

Instead of obtaining $V_\infty$ by the calculations outlined above, a graphical method originally described by Lang-

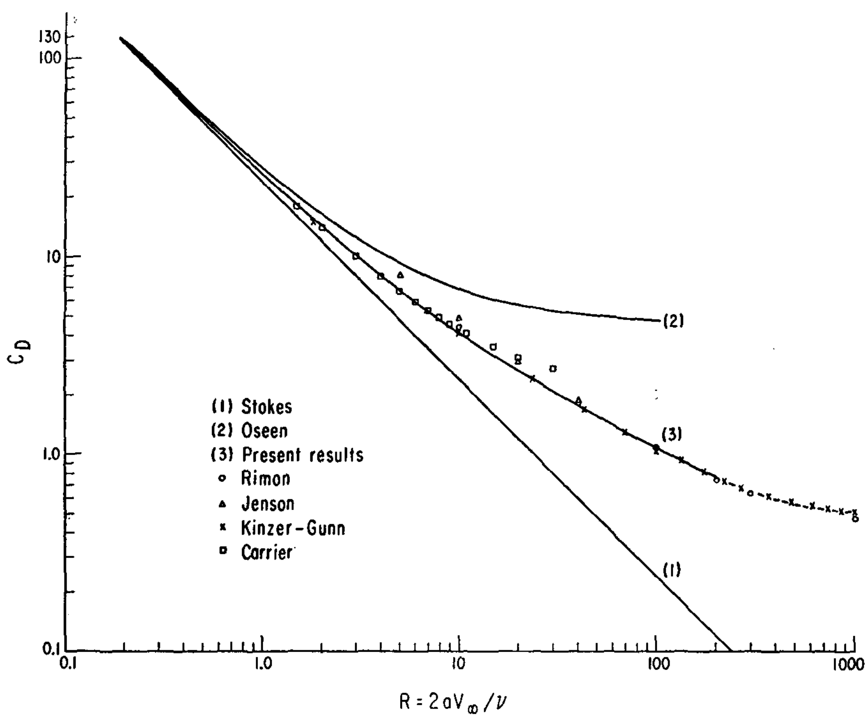


FIG. 4. Variation of the drag coefficient of water drops and spheres with Reynolds number.

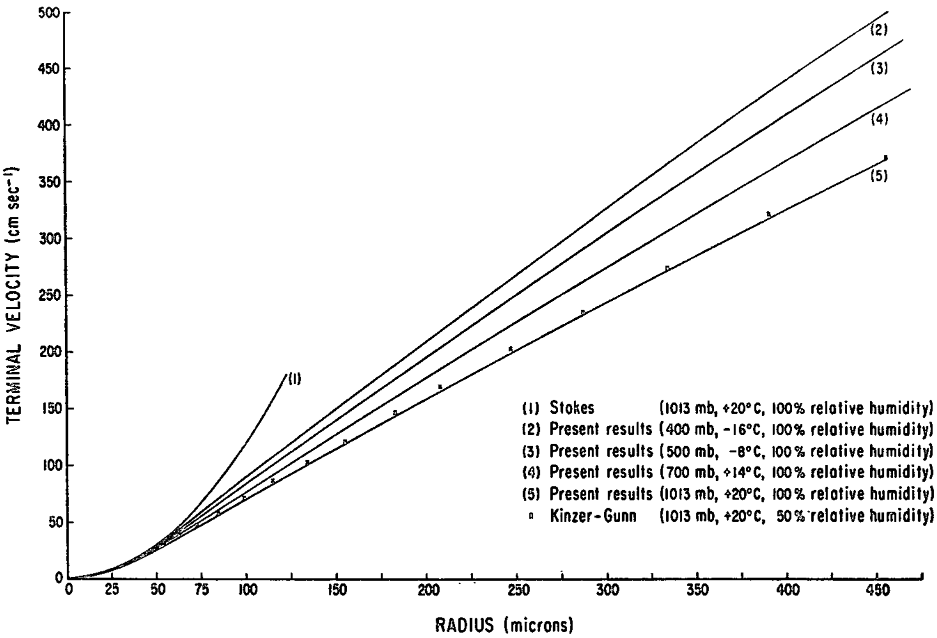


FIG. 5. Terminal velocity of water drops of various sizes and under various environmental conditions.

muir (1948) and further discussed by Mason (1957) and McDonald (1960) can be used. According to this method, $V_\infty$ of a drop of radius $a$ can be found for any atmospheric condition determined by $\rho_m$ and $\eta$ from a plot of $C_D\mathrm{R}^2$ vs R. The function $C_D\mathrm{R}^2$ is known from the empirical relations (18), (19) and (20), and Eq. (12). Values for $C_D\mathrm{R}^2$ as a function of R determined in this manner can be found in Table 1, from which $C_D\mathrm{R}^2$ can be plotted for any desired interval of R. On the other hand $C_D\mathrm{R}^2$ is readily derived from (13), i.e.,

$$C_D\mathrm{R}^2 = (32/3)a^3(\rho_s - \rho_m)(\rho_m g/\eta^2). \tag{24}$$

Given the drop size $a$ and the atmospheric conditions $\rho_m$ and $\eta$, $C_D\mathrm{R}^2$ can be computed from (24), the corresponding value of R read from the graph, and $V_\infty$ calculated from (15).

Our results show further, for $\mathrm{R} \leq 200$, that the drag on a water drop can be well represented by the drag on a sphere. Water drops having these Reynolds numbers must therefore have a shape which is close to spherical. For $\mathrm{R} > 200$ the drag of a drop becomes progressively larger than that of a sphere. This is an indication of its progressive departure from spherical shape.

An inspection of Fig. 5 shows that our values for the terminal velocities of water drops agree quite closely with those reported by Gunn and Kinzer, although Gunn and Kinzer's values appear to be slightly larger—in particular for small drops. This may be explained by the fact that in Gunn and Kinzer's experiment the environmental air in which the drops were falling was not water-saturated but had only a relative humidity of 50%; consequently, the drops must have been evaporating slightly as they fell. Since their size was determined at the end of fall, the terminal velocity of a drop of a particular size must have been overestimated. It is questionable, however, whether the deviation of Gunn and Kinzer's data from ours is indeed significant.

TABLE 1. Tabulation of numerical values for the quantity $C_D\mathrm{R}^2$ as function of Reynolds number R.

| R | $C_D\mathrm{R}^2$ | R | $C_D\mathrm{R}^2$ |
|---|---|---|---|
| 0.10 | 2.427 | 11.00 | 471.729 |
| 0.20 | 4.905 | 12.00 | 530.992 |
| 0.30 | 7.433 | 13.00 | 592.694 |
| 0.40 | 10.008 | 14.00 | 656.797 |
| 0.50 | 12.631 | 15.00 | 723.266 |
| 0.60 | 15.302 | 16.00 | 792.068 |
| 0.70 | 18.019 | 17.00 | 863.173 |
| 0.80 | 20.783 | 18.00 | 936.555 |
| 0.90 | 23.592 | 19.00 | 1012.189 |
| 1.00 | 26.448 | 20.00 | 1090.048 |
| 1.10 | 29.349 | 30.00 | 1887.708 |
| 1.20 | 32.296 | 40.00 | 2827.386 |
| 1.30 | 35.288 | 50.00 | 3887.765 |
| 1.40 | 38.326 | 60.00 | 5059.219 |
| 1.50 | 41.408 | 70.00 | 6334.488 |
| 1.60 | 44.536 | 80.00 | 7707.824 |
| 1.70 | 47.708 | 90.00 | 9174.488 |
| 1.80 | 50.924 | 100.00 | 10730.523 |
| 1.90 | 54.186 | 110.00 | 12372.516 |
| 2.00 | 57.491 | 120.00 | 14097.508 |
| 3.00 | 91.984 | 130.00 | 15902.863 |
| 4.00 | 129.560 | 140.00 | 17786.250 |
| 5.00 | 170.171 | 150.00 | 19745.578 |
| 6.00 | 213.685 | 160.00 | 21778.937 |
| 7.00 | 259.997 | 170.00 | 23884.559 |
| 8.00 | 309.997 | 180.00 | 26060.887 |
| 9.00 | 360.695 | 190.00 | 28306.445 |
| 10.00 | 414.948 | 200.00 | 30619.844 |

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