The NCAR Vertical Wind Tunnel:
A Vertical Wind Tunnel for Controlling
the Motion and Environment
of Atmospheric Particles

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This note describes a Vertical Wind Tunnel installed at the National Center for Atmospheric Research for cloud physics research. The Vertical Wind Tunnel has been referred to in some past correspondence and publications of the NCAR Cloud Physics Program by the descriptive title, Particle Control Chamber. The main purpose of this installation is to offset the vertical fall speed of cloud and precipitation particles with a low-turbulence, variable-speed, upward-moving column of air in which the temperature, moisture, and electrical environment can be controlled in a selected observable region of laboratory space. A secondary use is as a low-convection still-air chamber providing a long vertical column of controlled-environment air for the studies of freely falling particles and their interactions. In addition, the Vertical Wind Tunnel can be used for study and calibration of cloud physics instruments.

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INTRODUCTION

The NCAR Vertical Wind Tunnel (VWT) provides a vertically directed air flow that may be varied to control the vertical motion of particles, or to suspend particles for study. The environmental conditions may be varied over a range of temperature (-25 to +27°C), humidity (-45°C frost point to saturation at +27°C), electric field (0 to 1100 V cm\(^{-1}\)), and vertical velocity (1.25 cm sec\(^{-1}\) to 9.5 m sec\(^{-1}\)). The drop size that can be supported by the vertical flow varies from diameters of about 20 μm to about 5 mm. This wide range of variation permits duplication of environmental conditions so that water drops and ice particles and their interactions may be studied in the laboratory under environmental conditions similar to those found in nature.

This Technical Note describes the various characteristics of the VWT and its limitations. Sufficient detail is included for a potential outside experimenter to determine if his proposed experiment can be carried out in the VWT, and whether any additional instrumentation would be required.
I. INNER TUNNEL

The VWT was designed and built in two stages. First the basic inner tunnel was built, installed, and evaluated for performance at room temperature. Second, the environmental control equipment was designed and installed to provide temperature and humidity control for the inner tunnel. The VWT is located on the 4th and 5th floors and penthouse levels of Tower B at the Table Mesa laboratory of NCAR.

The inner tunnel is shown schematically in Fig. 1. The lower filter, honeycomb, riser, and screen sections are suspended from the contraction section support framework. This framework is attached to and supported by steel I beams at the 5th floor level. Leveling screws are provided to permit adjusting the plumb of the test section and everything below it. The upper diffuser, screen, and honeycomb, and the upper riser are supported at the penthouse floor level. This supporting structure permits everything above the test section to be adjusted for plumb with leveling screws, and to be moved horizontally (to permit precise alignment of the upper diffuser with the test section) and vertically (to permit removal of the test section and to compensate for expansion and contraction). The upper diffuser tapers slightly, providing a transition from the 27.94-cm (11 in.) square test section to the 30.58-cm (12 in.) square screen, honeycomb, and riser sections.

The contraction section has an area contraction ratio of 7 to 1 and a shape designed to insure low turbulence flow in the test section.¹

¹The shape of the contraction section was computed on a theoretical basis by the Inca Engineering Corporation after the design had proven practical in the UCLA Cloud Tunnel (Pruppacher and Neiburger, 1968).
Fig. 1 Schematic diagram of the inner tunnel, showing the relative locations of the various components.
Experiments are performed in the test section, a transparent parallelepiped 121.9-cm (48 in.)-high and 30.48 cm (12 in.) square outside cross section. It is made of 1.27-cm (1/2 in.)-thick Lucite to permit visual observation and photographic recording. As shown in Appendix C, the test section comprises three individual segments, each 40.64 cm (16 in.) high. In each segment a removable panel is provided for access to the interior and for mounting of probes for measuring airspeed, humidity, and temperature as well as for mounting drop-makers or other apparatus.

The overall height of the inner tunnel is 8.84 m (29 ft). The top of the upper riser is 30.48 cm (12 in.) square, and the lower riser is 73.91 cm (29.1 in.) square. All metal surfaces are primed and painted to prevent rust.
II. ENVIRONMENTAL CONTROL

The design specifications for the test section required that temperature be varied from -20 to +20°C, with the dew-point variable from -40°C to saturation. These conditions were required at flow rates ranging from 1.25 cm sec$^{-1}$ to 9.5 m sec$^{-1}$. A closed-circuit configuration was chosen to eliminate the effects of changing building pressure, to eliminate overloading the building's air conditioning system, and to increase the efficiency of temperature and humidity control when the equipment is operating above 0°C.

A schematic diagram of the complete VWT is shown in Fig. 2. The inner tunnel is enclosed in a shroud which is supplied with the same air as the test section, eliminating any convective turbulence inside the test section that would result if there were a temperature differential across its walls.

The operation of the environmental control equipment may be followed by reference to Fig. 2. The fan moves the air past the humidifier and through the diffuser to the shroud. A portion of the air moves upward through the shroud and past the test section to the lower chamber of the air valve, while another portion moves down the shroud, is turned through 180° by turning vanes (not shown) and rises through the class 100 absolute filter (which removes all particles larger than 0.3 μm in diameter with an efficiency of 99.999%), honeycomb, and screens. This air proceeds upward through a contraction section, through additional screens and honeycombs, and back down the upper part of the shroud to the upper chamber of the air valve. A bypass duct
Fig. 2 Schematic diagram of VWT, showing the shroud and the environmental control equipment.
is provided to bypass part of the shroud air when very low test section velocities are required so that excessive turbulence is not generated by high flow velocities through the shroud.

The air flow control valve is of the double-tapered plug type. Moving the two plugs upward together will increase the flow in the shroud while decreasing the flow in the test section, with the total flow remaining constant. Moving one plug relative to the other will adjust the total flow so that the total mass flow can be held constant as the environmental conditions are changed.

The air leaving the flow control valve passes through the methylene chloride precooling coil and the small cooling coil, and proceeds to the drying unit. The methylene chloride precooling coil is part of a heat exchanger system; the other end of the system is the methylene chloride heating coil located at the exit of the drying unit. By proper adjustment of the methylene chloride bypass valve, the heat removed from the air by the precool coils and reintroduced by the heating coil may be varied.

The small cooling coil is used when the equipment is operating above 0°C to compensate for the heat added to the circulated air by the blower and the steam. It is not intended to be in operation when the large compressors are being used. The drying unit uses a lithium chloride desiccant solution (trade name Kathene) which is sprayed over the two large cooling coils. The use of a liquid desiccant eliminates the dust problem found in many dry systems and removes particulate matter that may have found its way into the airstream.
Moisture is removed from the desiccant by heating it with a steam heater in the regenerator unit. This regeneration process can be carried out when the VWT blower is not running, if necessary, to conserve steam.

After drying and cooling, the air passes the methylene chloride heating coils, then proceeds to the fan and humidifier, repeating the cycle. The humidifier is the superheated steam type. Deionized and filtered water is heated in a glass-lined boiler to make steam which is transferred to the humidifier in a stainless steel pipe to maintain purity.

All of the environmental conditions are controlled from a central panel located near the test section on the fifth-floor level. The environmental conditions are monitored from instruments located near the central control panel (See Appendix A for available instrumentation). The control panel is shown on the left side of Fig. 3. The shrouded test section is in the center and the air valve controls are seen between the control panel and the test section.

A better understanding of the contribution each piece of equipment makes to the overall operation of the system may be obtained by referring to Fig. 4, which illustrates the various ranges of operation. Region A, in the upper right portion of the figure, is reached by using the small compressor alone. Temperature is controlled by the electric heater and humidity by varying the amount of steam injected into the airstream. The drying unit may or may not be used in this region. If long periods of operation at very high humidities are planned, the drying unit should not be used; it should, however, be turned on at the end of
Fig. 3 A view of the VWT taken at the fifth floor level. The main control panel is at the left of the photograph, the shrouded test section is in the center, and the air valve controls are seen between the control panel and the test section.
Fig. 4 An illustration of the three regions of operation of the VWT. Region A is the area of operation using only the small compressor. Region B is the area of operation using one of the large compressors. Region C is the area of operation with two large compressors. See text for further explanations.
the run to dry out the air in the tunnel. Much smaller quantities of
steam are required for high humidities with the drying unit off.

With only the small compressor operating, the air will stabilize
at the lower left corner of Region A. Adding steam will cause the dew-
point to rise along the left-hand boundary of this region. Adding
electric heat (without steam) will cause the air temperature to move
to the right along the lower boundary of this region. By use of steam
and electric heat any of the points within Region A can be reached.

Region B, in the middle of Fig. 4, shows the range of operation
when using either one of the large compressors for cooling. Since the
cooling coil temperature will be below 0°C in this region, the drying
unit must be used to prevent the buildup of ice on the cooling coils.
With just one large compressor and the drying unit operating, the
test section air will stabilize at the lower left corner of the region.
By injecting steam to add humidity the dry-bulb temperature will
increase slightly (due to the heat of the steam) and the humidity will
increase, proceeding up the left-hand boundary of the region. Con-
versely, if no steam is injected into the air stream but electric heat
is added, the dry-bulb temperature will proceed to the right along the
bottom boundary of the region until it reaches point b in the diagram.
At point b the electric heating coils are operating at capacity, and
the methylene chloride heat exchanger must be used to increase the dry-
bulb temperature further. The temperature may be varied between points
b and b' by adjusting the methylene chloride bypass setting. With full
methylene chloride heat exchanger operation and proper adjustments of the electric heater and steam, the dry-bulb temperature may be increased to the right-hand edge of Region B.

Proper adjustment of the steam, methylene chloride heat exchanger, and electric heat will permit operation anywhere in Region B. Furthermore, operation with one large compressor can be carried over into Region A, although this is not an efficient mode of operation. For example, if it were desired to calibrate a humidiometer at a dry-bulb temperature of 15°C, while the dew- or frost-point temperature was being varied from -25 to 0°C, it would only be necessary to start at the lowest frost-point (bottom of vertical dashed line in Fig. 4) and move upward by increasing the steam flow until the calibration was completed. The inefficient operation near the dew-point temperature of 0°C is offset by the time saved in not having to disturb the operation in a major way by switching compressors and then having to establish equilibrium.

Operation in Region C is analogous to that described above for Region B except that both large compressors are used. The same considerations of efficiency also apply to moving into Region B from Region C.

It is necessary to plan the operation of the VWT for a particular experiment carefully in order to avoid time-consuming delays. For example, if the large compressors had been turned on for an experiment and were then turned off for any reason, these machines must not be restarted until their suction temperature is above 0°C. It requires
at least 4 hr, or preferably overnight, for the suction temperature to rise above 0°C, permitting any condensed refrigerant to evaporate so that the machine can be restarted.

The time required for the VWT to become stable after being started up is a function of the starting and ending points. For example, starting with the system stabilized at a room temperature of 24°C (that is, everything turned off) 50 min are required for the test section conditions to stabilize at 20°C. To get to -20°C from the same initial conditions requires 120 min. Small changes in temperature or humidity will stabilize in about 20 min. After the VWT has stabilized to a given set of conditions, the temperature and dew-point will remain within about ±0.2°C of that value. Several hours of running at required wet- and dry-bulb temperatures may be necessary to reduce convection currents to the point where small drops can be floated out in a satisfactory manner.
III. CONTROL OF THE ELECTROSTATIC FIELD WITHIN THE TEST SECTION

A structure made up of eight conducting loops, electrically connected by matched five-gigaohm resistors, was placed inside the test section to create a vertical electrostatic field. The loops are made from 1.27-cm (0.5 in.)-wide aluminum tape attached to the inside of the test section with 15-cm center-to-center vertical spacing. The test section is shown in Fig. 5 with the loops and resistors installed. One or more sections can be connected across a high voltage supply to create a field of desired strength and known uniformity. With a potential of 40 kV across all seven resistors, the field is about 330 V cm\(^{-1}\). With 40 kV across only one resistor, a field of 1100 V cm\(^{-1}\) exists at the very center of the test section, but this field is not very uniform. Higher field values can be obtained with a higher voltage supply.

Calculations were made to determine relative field strength and uniformity throughout the test section interior for various numbers of resistors. The mathematical analysis and some results of the calculations are presented in Cannon and Davis (1971); the calculations are made for rings of circular cross section, but a solution to Laplace's equation for an infinite structure of square loops of elliptical cross section shows that the ring calculation is adequate for the square loop case as long as the thickness of the conductor is small relative to its height.

Figure 6 shows the equipotential lines (the solid lines) for the N = 8 conductor case; only half of the field is shown since it has symmetry about the midplane. Table 1 shows the magnitude of the field as
Fig. 5 Test section with field-producing structure installed. Loops are made of 1.27-cm (0.5 inch)-wide aluminum conducting tape and have 15 cm (5.91 inch) center-to-center vertical separation. The loops are connected by five gigaohm resistors shown in the left hand corner.
well as calculated values of its uniformity for $2 \leq N \leq 8$ conductors over a cylindrical test volume of radius 7.3 cm and overall height 30 cm centered at the midpoint of the test section.

Fig. 6 Electric field map for $N = 8$ conductor configuration used to produce the electric field in the test section. Only the upper half of the field is shown, the lower half being a mirror image. Solid curved lines are equipotential lines with contour interval of 0.2 units of the field across the resistors; dotted lines are the electric field lines.
TABLE 1

CALCULATED CHARACTERISTICS OF THE ELECTROSTATIC FIELD WITHIN A CYLINDRICAL TEST VOLUME OF RADIUS 7.3 CM AND A HEIGHT OF 30 CM CENTERED AT THE MIDPOINT OF THE TEST SECTION

| N  | $|E|_{av}$ | $\Delta E$ | $\Delta \beta$ |
|----|-----------|-----------|-----------|
| 2  | 0.226     | 2.17      | 2.62      |
| 3  | 0.491     | 0.952     | 0.351     |
| 4  | 0.666     | 0.400     | 0.0366    |
| 5  | 0.771     | 0.193     | 0.0569    |
| 6  | 0.815     | 0.109     | 0.0215    |
| 7  | 0.847     | 0.0930    | 0.0285    |
| 8  | 0.859     | 0.0751    | 0.0202    |

$N$ = number of conducting loops used to generate the field

$|E|_{av}$ = average magnitude of field expressed as a multiple of the field across the resistors.

$|E|_{max}$ = maximum magnitude of the electric field expressed as a multiple of the field across the resistors.

$|E|_{min}$ = minimum magnitude of the electric field expressed as a multiple of the field across the resistors.

$\beta_{av}$ = average value of the angle between the electric field vector and the vertical axis.

$\beta_{max}$ = maximum value of the angle between the electric field vector and the vertical axis.

$\beta_{min}$ = minimum value of the angle between the electric field vector and the vertical axis.

$\Delta E = \frac{|E|_{max} - |E|_{min}}{|E|_{av}}$

$\Delta \beta = \frac{\beta_{max} - \beta_{min}}{\beta_{av}}$
IV. OPERATION AS A VERTICAL STILL AIR COLUMN

The VWT has provisions for operation as a Vertical Still Air Column (VSAC). In this mode of operation, the airflow in the test section is blocked off by inserting a blocking cartridge at the top of the contraction section, and replacing the screen and honeycomb sections at the penthouse level with open sections as shown in Fig. 7. The insert is removed from the valve spool to permit bypass air to enter the shroud at the top, cooling the upper portion of the vertical still air column. An apparatus box can be placed on top of the vertical riser to house drop-makers or other apparatus. The temperature of the still air chamber is controlled by the air temperature of the shroud, and is variable over the same range of temperatures as the VWT.

The maximum vertical fall is 5.64 m (18.5 ft). At the top the inside dimensions are 30.48 cm (12 in.) square while the bottom end is 27.94 cm (11 in.) square. The bottom 121.92 cm (48 in.) is transparent plastic (the VWT test section).
Fig. 7 Schematic diagram of Vertical Wind Tunnel, showing the modifications necessary to convert it to a Vertical Still Air Column.
V. EXPERIMENTAL CAPABILITIES

Each of the three segments of the test section may be removed separately, and a new segment suitably modified for a given experiment may be substituted. Although the present test section is made of 1.27-cm (0.5 in.)-thick lucite, other materials may be used if the experiment requires it, and if the inside dimensions and mounting flange dimensions are preserved. In the event that low temperature operation is planned, some consideration must be given to expansion and contraction of other materials. Detailed drawings of one segment of the test section are shown in Appendix C. If heavy objects need more support than can be obtained from the test section walls, additional bracing may be obtained from the shroud panels.

Provision has been made to insert drop-makers or spray nozzles into the contraction section just above the fifth-floor level (see Fig. 2 for the location of this portal). The access portal covers an opening that is 25.4 cm (10 in.) high and 20.35 cm (8.010 in.) wide. The bottom of the opening is 73.91 cm (29.10 in.) below the bottom of the test section.

Introduction of drops into the airstream at this access portal provides a longer path for approaching thermal equilibrium with the air by the time they reach the position of the test section where the measurements are made. It must be pointed out that objects inserted at this level should be kept as small as possible to prevent introducing excessive turbulence in the test section.
Individuals contemplating experiments in the VWT are advised to discuss their specific requirements with NCAR personnel before scheduling time for an experiment. Profiles of dry- and wet-bulb temperature, turbulence, and velocity vs position in the test section are kept on file and should be studied to determine the feasibility of performing any contemplated experiment in the VWT.

It is often convenient, while working with drops, to have information on terminal velocities, Reynolds numbers, drag coefficients, and other parameters for the drop sizes of interest. As a convenience for experimenters, much of this information has been tabulated in Appendix B.
APPENDIX A

AVAILABLE INSTRUMENTATION

The instrumentation described below is available for use with the NCAR Vertical Wind Tunnel. Each instrument is described, its range stated, and its accuracy discussed. In some cases, the accuracy stated is simply what the manufacturer claims; in other cases a more careful determination of accuracy has been made, and is so indicated.

DEW-POINT MEASUREMENT

The Cambridge Systems, Inc. Model 992-C1 Dew-Point Hygrometer is used for measuring the humidity in the VWT. A 100-ohm platinum resistance thermometer (Rosemount 118F RTD) and a DORIC DS-100-T5 digital thermometer readout are used to monitor the dew-point temperature. The range is from -40 to +40°C, with 0.01°C resolution. Accuracy of the temperature determination is 0.04°C or better, relative to the 1948 Internal Practical Temperature Scale. The largest contributor to error in the measurement of dew-point with the above system is the sample line error which, for the existing system, varies from +0.094°C error at -40°C to +0.211°C error at +30°C. These errors can be estimated, and the data corrected, if necessary. Another source of error is the formation of individual ice crystals on the mirror at low frost-point temperatures (Dye, 1973). The output of the DORIC is recorded and displayed on the Leeds and Northrup chart recorder discussed below.
TEMPERATURE MEASUREMENT

A DORIC DS-100-T digital thermometer readout with platinum resistance (Rosemount 118F RTD) is available for use as a remote-probe and comparison standard. The platinum resistance is mounted on the end of a probe which has a sliding sleeve to protect the element. The resolution and accuracy of this system is the same as the DORIC system discussed in the previous paragraph.

Routine temperature measurements at various locations are made with copper-constantan thermocouples and a Leeds and Northrup Speedomax 12-point recorder, calibrated from -40 to +40°C. All 12 points are currently connected. However, only half of these are actually necessary for monitoring the operation of the VWT. The rest are available for use in experiments if necessary. The long-term accuracy of this recorder has not been established. However, the platinum resistance thermometer described in the previous paragraph is available for comparison readings.

Temperature measurements may also be made with a Flow Corporation Model 700-3042 Hot Wire Anemometer System. The system has a range of +100°C, and an accuracy of 0.5°C.

VELOCITY MEASUREMENTS

Several methods are available for measuring the mean velocity of air in the test section. The most convenient is the Hastings Model B-22 Air Meter with a Hastings Type 5-22A probe. It measures the air velocity over the ranges of 0 to 2.54 and 2.54 to 50.8 m sec^{-1} (0 to 500 and 500 to 10,000 ft min^{-1}). The accuracy of this instrument is
not specified by the manufacturer. With careful use, its accuracy is believed to be $\pm 3\%$ of the reading. This instrument is subject to the same limitations of most thermocouple devices at very low velocities: it is difficult to obtain an unambiguous calibration curve.

For use at low velocities, a Thermo-Systems Model 4100 IONFLO Airflow meter is available. This instrument has a resolution of $\pm 0.50 \text{ cm sec}^{-1}$ (1.0 ft min$^{-1}$) with an accuracy of $\pm 1\%$ of reading and $\pm 0.05\%$ of range over the velocity of range of 0.005 to 10.15 m sec$^{-1}$ (1 to 1999 ft min$^{-1}$). In order to achieve this accuracy, the readings must be corrected for dew-point temperature.

Also available is a pitot-static tube based on the standard National Physical Laboratory design (Ower, 1949). This design results in a tube whose factor is 1.0 correct to 0.1% for velocities greater than 1 m sec$^{-1}$. Two readout devices are available for use with this pitot-static tube: a DISA Hero Mocromanometer that measures small pressure differences to a resolution of 0.01 mm of liquid column and a Statham Laboratories Model PM 197TC $\pm 0.01-350$ temperature-compensated pressure transducer. The accuracy and resolution of the tube are determined by the particular readout device used.

Updraft velocities less than 1 m sec$^{-1}$ may also be determined by the Abbott method (Abbott, 1973), which uses the collision and coalescence of two droplets of equal radii and the subsequent velocity change.
DROP-MAKERS

A number of different systems have been tried for generating drops in the test section. When drops of uniform size and known charge are required, the Abbott-Cannon droplet generator is available (Abbott and Cannon, 1972). These generators can produce droplets continuously, one at a time, or in groups of two or more droplets with adjustable production rate of up to 100 sec$^{-1}$ for the smallest sizes. Size, charge, and time of production may be changed electronically from droplet to droplet. The droplet size range covered is 4 to 375 μm in radius. The drop generator will operate over the temperature range of the VWT, provided the reservoir is heated when test section temperatures are below 0°C.

Also available is an impact nebulizer for producing a continuous cloud of droplets. The droplets produced are in the range of 10 to 100 μm in diameter. The spectrum has not yet been determined.
APPENDIX B

PROGRAM DRØP

Several hydrodynamic parameters applicable to rigid spheres and pertinent to Vertical Wind Tunnel experiments are calculated using the NCAR computer program DRØP. The main body of this program was obtained from UCLA through the courtesy of K. V. Beard. A section for calculating relaxation times and stop distances for Reynolds number $R \leq 1.0$ was added at NCAR.

The parameters calculated by DRØP are terminal velocity, $V_\infty$; radius, $a$; drag coefficient, $C_D$; $(D/D_s)^{-1}$ where $D = \text{drag force and } D_s = \text{Stokes drag force}$; sphere volume, $V_{\text{ol}}$; mass, $m$; relaxation time, $\tau$; and stop distance, $\lambda_1$. These values are calculated for incremented values of Reynolds number. $V_\infty$ is plotted by the computer against $a$; $C_D$, $(D/D_s)^{-1}$, $V_{\text{ol}}$, and $m$ are plotted against $R$ for $R \leq 250$; and $\tau$ and $\lambda_1$ are plotted against $R$ for $R \leq 1.0$. These plots are made for input values of pressure in millibars ($p$), dew-point temperature in degrees $C(T_D)$, and dry-bulb temperature in degrees $C(T_C)$.

Values of sphere density, $\rho_s$, medium density, $\rho_m$, and medium viscosity, $\eta$, are calculated by the program for the input values of $p$, $T_D$, and $T_C$. 
Calculations are made using the following equations:

1. \( \frac{D}{D_s} \) is calculated using

\[
\frac{D}{D_s} = 1 + \left( \frac{3}{16} \right) R \quad \text{for} \quad R < 0.01 \quad \text{Oseen formula}
\]

\[
\frac{D}{D_s} = 1 + 10^x \quad \text{for} \quad 0.01 < R \leq 20.0
\]

LSF to numerical data of Le Clair where

\[
x = -0.8810 + 0.8222w - 0.05189w^2 \quad \text{and}
\]

\[
w = \log_{10} R
\]

\[
\frac{D}{D_s} = 1 + 0.189R^{0.632} \quad \text{for} \quad 20.0 < R \leq 258
\]

LSF to numerical data of Beard - Pruppacher.

2. \( C_D \) is calculated from

\[
C_D = \left( \frac{24}{R} \right) \left( \frac{D}{D_s} \right)
\]

3. \( C_D R^2 \) is calculated directly from \( C_D \) and \( R \)

4. The drop radius, \( a \), is calculated as follows:

\[
\frac{1}{2} \rho_m v_\infty^2 \pi a^2 C_D = \frac{4}{3} \pi a^3 (\rho_s - \rho_m) g
\]

\[
R = \frac{2a \rho_m v_\infty}{\eta}
\]

Substituting \( v_\infty \) from the second equation into the first and solving for \( a^3 \) we obtain

\[
a^3 = \frac{3\eta^2 R^2 C_D}{32\rho_m (\rho_s - \rho_m) g}
\]
5. Terminal velocity, $V_\infty$, is calculated from

$$V_\infty = \frac{nR}{2\rho_m a}$$

and this equation is simply the expression

$$R = \frac{2\rho_m V_\infty}{\eta}$$

solved for $V_\infty$.

6. The volume of the drop is calculated from

$$\text{Vol} = \frac{4}{3}\pi r^3$$

7. The mass of the drop, $m$, is Vol times $\rho_s$.

8. The relaxation time is calculated for $R \leq 1.0$ only from Eq. 17-3, of Fuchs (1964, p. 71):

$$\tau = \frac{2\rho_s a^2}{9\eta}$$

$\tau$ is defined as the time for a sphere moving at some initial velocity to reach $1/e$ of that velocity after all forces but the Stokes drag force are removed.

9. The stop distance is calculated from Eq. 17-18 of Fuchs (1964, p. 73) for $R \leq 1.0$ only as

$$l_i = \tau V_\infty$$

and is the limiting distance a particle will travel if it has initial velocity $V_\infty$ and all forces but the Stokes are removed.
As examples and for reference, plots of $V_\infty$ vs $a$ and $a$ vs $R$ for $0.003 \leq R \leq 9.0$ are shown in Figs. 8 through 13 according to the following table.

<table>
<thead>
<tr>
<th>$T(°C)$</th>
<th>$T_D(°C)$</th>
<th>Figure for $V_\infty$ vs $r$</th>
<th>Figure for $R$ vs $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-30</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>-20</td>
<td>-20</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

Figs. 14 through 19 show $(D/D_s^{-1})$, $C_D$, $\tau$, $\bar{\lambda}$, $m$, and Vol for the $T = 20°C$, $T_D = -20°C$ case.

These plots were made for $p = 821$ mb, the approximate average pressure at the tunnel location. The program is only useful for $R \leq 258$ as valid values of $(D/D_s)$, since higher values of $R$ are not included in the program. $\tau$ and $\bar{\lambda}$ are calculated for $R \leq 1.0$ only.

Analytical expressions for the velocity and distance traveled as a function of time for accelerating drops with Reynolds numbers less than five are given by Sartor and Abbott (submitted 1974).
Fig. 8 Terminal velocity $V_\infty$ vs drop radius $a$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -30^\circ C$, and pressure $p = 821$ mb.

Fig. 9 Radius $a$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -30^\circ C$, and pressure $p = 821$ mb.
Fig. 10 Terminal velocity $V_\infty$ vs drop radius $a$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = 20^\circ C$, and pressure $p = 821$ mb.

Fig. 11 Radius $a$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = 20^\circ C$, and pressure $p = 821$ mb.
Fig. 12 Terminal velocity $V_\infty$ vs drop radius $a$ for water drops at dry-bulb temperature $T = -20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.

Fig. 13 Radius $a$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = -20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.
Fig. 14  \((D/D_d)^{-1}\) vs Reynolds number \(R\) for water drops at dry-bulb temperature \(T = 20^\circ\text{C}\), dew-point temperature \(T_D = -20^\circ\text{C}\), and pressure \(p = 821\) mb.

Fig. 15  Drag coefficient \(C_D\) vs Reynolds number \(R\) for water drops at dry-bulb temperature \(T = 20^\circ\text{C}\), dew-point temperature \(T_D = -20^\circ\text{C}\), and pressure \(p = 821\) mb.
**Fig. 16** Relaxation time $\tau$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.

**Fig. 17** Stop distance $x$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.
Fig. 18 Mass $m$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.

Fig. 19 Volume $Vol$ vs Reynolds number $R$ for water drops at dry-bulb temperature $T = 20^\circ C$, dew-point temperature $T_D = -20^\circ C$, and pressure $p = 821$ mb.
APPENDIX C

TEST-SECTION DRAWINGS

Figure 20 is a detailed drawing of one segment of the test-section and a test-section door. The existing test section is made of Lucite; other materials may be used if the experiment requires it. Three segments make up the entire test section.

Figure 21 is a drawing of the access panel for the contraction section. Several interchangeable panels are available as of this writing. The existing panels are made of mild steel, and have been sprayed with clear acrylic lacquer for protection against rust. Other panels may be made of other materials should the experiment require it, but expansion and contraction should be taken into account.
Fig. 20 Drawing of segment of test section. Test section is made up of three identical segments.
Fig. 21 Drawing of portal door for contraction section.
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