THE UTIAS PRECIPITATION WIND TUNNEL

by

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Summary

A description is given of the design, construction and calibration of a closed circuit wind tunnel, specially designed for studying the aerodynamic behaviour of precipitation (rain or snow) falling in a side wind blowing about buildings or other structures.

The tunnel has a test section of 3-1/2 ft. by 3-1/2 ft. by 16 ft., and a maximum wind velocity of about 10 ft/sec. The particles selected to simulate rain and snow are spherical glass beads having diameters in the 20 to 150 μm range. In an Appendix a review is given of the current knowledge of the aerodynamics of precipitation.
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\[ A_p \]  
particle frontal area

\[ \text{BHP} \]  
motor brake horse power

\[ C_d \]  
drag coefficient

\[ d_e \]  
equivalent drop diameter

\[ d_p \]  
particle diameter

\[ D_p \]  
particle drag

\[ E_{R_t} \]  
tunnel energy ratio

\[ g \]  
gravitational acceleration

\[ I_p \]  
particle volume

\[ k \]  
\[ \frac{1}{8} C_d \rho \pi d_p^2 \]
component loss parameter

\[ K_o \]  
characteristic particle length

\[ l_p \]  
characteristic length

\[ m \]  
particle mass

\[ \Delta p \]  
static pressure drop

\[ \Delta p_{dv} \]  
pressure difference in double venturi static - pitot tube instrument

\[ q_o \]  
test section dynamic pressure

\[ q_{st} \]  
Subsonic Wind Tunnel test section dynamic pressure

\[ Q_o \]  
test section volume flow

\[ \text{Re} \]  
Reynolds number

\[ t \]  
nozzle thickness; time

\[ u \]  
particle velocity components relative to ground

\[ \{ u, v \} \]  

\[ w \]  
fluid velocity components relative to ground

\[ \{ w' \} \]  

\[ v \]
velocity
jet velocity
test section speed
particle velocity relative to air
Subsonic Wind Tunnel test section speed
terminal velocity
wind velocity
fan efficiency
viscosity
micron (10^{-6} m)
kinematic viscosity
dimensionless groups of variables
dimensionless groups of variables
air mass density
particle mass density
"hat" - symbol identifying non-dimensional quantities
I. INTRODUCTION

One of the many areas in the extensive field of physics of the atmosphere concerns the aerodynamic behaviour of the precipitate particles rain, snow, and hail, falling to the earth surface along often very complicated trajectories. Considerable research has already been performed on this subject, mainly regarding blowing snow and particle terminal velocity, but a growing need exists for more understanding of the phenomena.

The ever-increasing size and complexity of buildings and constructions of conventional and novel design (such as the "dynamic structures" made up of air jets, see Refs. 25, 26, 29), make it highly desirable that the interaction between structure and atmospheric environment can be predicted and calculated to a reasonable degree of accuracy by means of machine computation.

For some time now attempts have been made at the Institute for Aerospace Studies to compute trajectories of particles falling through a horizontal air jet (Refs. 25, 31), and particles falling through a vertical air jet issuing into a normal cross wind (Refs. 3, 24). Some exploratory experiments using drops of milk and water have also been performed, see Refs. 24, 25, 37. The results of these investigations appear to be encouraging, and a need is felt for more fundamental information on the aerodynamic behaviour of particles. As full scale research is mostly very difficult and very costly to execute, adequately modelled experiments in special research facilities such as wind tunnels would be very advantageous.

Although many wind tunnels are being used the world over for various kinds of research concerning the interaction between structures and non-particulate air flows (see for instance Refs. 6, 52, 53), the author does not know of any wind tunnel in which the trajectories of particles falling in an arbitrary side wind have been modelled. The few wind tunnels and water flumes used to investigate the properties of blowing snow are not suitable for measuring particle paths, and they have been used almost exclusively for investigations concerning the accumulation and deposition of drifting snow.

A special wind tunnel with a 3-1/2 ft. x 3-1/2 ft. x 16 ft. test section and a maximum velocity of about 10 ft/sec has therefore been designed and built at UTIAS to investigate the interaction between wind, falling particle, and model building (either solid or gaseous), using tiny glass beads for simulating the precipitate particles. In the present report the reasoning behind the design is given, together with a description of the tunnel circuit and the basic instrumentation and operational methods used. The cost of the tunnel, exclusive of labour, amounted to about $3300.00. The tunnel was put into operation in April 1972. A first series of tests on the penetration of glass beads through an annular air dome is described in Ref. 36.

The Appendix presents an introductory review of the current knowledge on the aerodynamic properties of rain, snow and hail, based on a study of a number of representative publications.

II. DISCUSSIONS OF TUNNEL DESIGN

II.1 Design Requirements

-- the available space in a 30 ft. x 120 ft. closed laboratory room with an
11 ft. height is about 15 ft. x 50 ft. x 11 ft.;

-- the tunnel must be reasonably inexpensive to build, and easy to operate and maintain;

-- the construction should be simple and curved surfaces should be avoided where possible;

-- the tunnel must be assembled from prefabricated components which are small and light enough to be handled by two men;

-- avoid welding, cementing, and riveting, but use bolts, nuts, and screws instead;

-- the test section should be as large as possible;

-- as there is not enough room to install a contraction in front of the test section, other methods must be used to ensure adequate flow quality;

-- the tunnel interior must be easily accessible for installation and maintenance of models and instrumentation;

-- the quality of the very low energy level air flow must not be influenced by outside disturbances such as people walking by and opening and closing of doors and windows in the laboratory room;

-- during operation the noise level outside the tunnel should be low enough not to be a nuisance;

-- ample facilities for visually observing the flow phenomena must be incorporated in the design;

-- it is not necessary to minimize power consumption, because only very little power will be required to drive the low velocity air flow;

-- a simple and convenient method must be developed to accurately measure and set the tunnel speed; once set, this speed must remain stable and not exhibit drift;

-- it must be possible to generate various required velocity profiles and turbulence intensities of the test section flow;

-- the two main problems concerning the modelling of particles, i.e., deriving the scaling laws, and finding a suitable simulation material, must be solved;

-- the size, shape and terminal velocity of the particles selected to simulate the precipitation must be determined;

-- a technique must be developed to introduce the particles into the tunnel flow at a known repeatable rate and at different locations;

-- very small particles that remain suspended in the tunnel air must be filtered out before entering the return duct.
II.2 Modelling Considerations

The scaling laws governing model experiments can be investigated by means of dimensional analysis, see for instance Ref. 50. The two techniques that will be applied in the following study, and which will lead to partly overlapping results, are dimensional analysis using the Buckingham Pi-theorem, and dimensional analysis by non-dimensionalizing the basic equations of motion. These methods will be used in the three-dimensional situation of particles falling in a wind stream which flows about an obstruction made up of appropriately shaped air jets, called a "dynamic structure" (see Section A.1.2 of the Appendix).

The following discussion is essentially the analysis presented by Etkin and Lake in Refs. 24 and 37, which appears to be a good approximation and to give useful results in spite of a number of simplifications. The analysis gives an insight into the basic nature of the particle-flow interactions, and emphasizes the importance of various dimensionless groupings of variables. It provides sufficient information for designing the precipitation wind tunnel and the models to be used. (Some insight into various refinements, such as the scaling of velocity distribution and turbulence, can be obtained from the studies on the scaling laws of blowing snow presented in Refs. 33, 44, 46, 61. An introductory discussion on the modelling of rain impingement on buildings is given in Ref. 28).

Pi-theorem

The falling particles are rigid and geometrically similar, and characterized by the diameter $d_p$ and the density $\rho_p$. The velocity of the air stream relative to the ground is $W$, and the air density and viscosity are $\rho$ and $\mu$ respectively. The air jet structure has a characteristic length $L$, a nozzle thickness $t$, and a jet velocity $V_j$ at the nozzle exit; its density and viscosity are again $\rho$ and $\mu$. Together with the gravitational acceleration there are then nine relevant variables: $V_j, t, L, W, d_p, \rho_p, \rho, \mu, g$, which are related by the basic equation $f_1(V_j, t, L, W, d_p, \rho_p, \rho, \mu, g) = 0$. The Pi-theorem states that there are $9-3 = 6$ dimensionless groupings of these variables which completely represent the particle-flow field, and which are represented by the equation

$$f_2(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) = 0$$

Experience and intuition lead to the following choice of non-dimensional pi-groups:

$$\pi_1 = \frac{\rho}{\rho_p}$$

$$\pi_2 = \frac{V_j}{W}$$

$$\pi_3 = \frac{t}{L}$$

$$\pi_4 = \frac{d_p}{L}$$

$$\pi_5 = \frac{V_j t \rho}{\mu}$$

($\pi_5$ is Reynolds number)

$$\pi_6 = \frac{V_j^2}{Lg}$$

($\pi_6$ is Froude number)
For model and full scale flows to be dynamically similar, these six groups must be the same in both cases, but to meet these similarity conditions simultaneously would obviously be difficult if not impossible. Fortunately these conditions appear to be unduly restrictive as will be shown in the following analysis.

Non-dimensional equations of motion

This method arranges the parameters into the minimum number of dimensionless groups that can be used to describe the problem; it combines some of the six pi-groups mentioned above into a smaller number of dimensionless groups.

The simplified equations of particle motion will now be derived and non-dimensionalized. (Publications on general equations of motion are mentioned in the Appendix). The particles having mass \( m \) are assumed to be solid spheres, suspended in an arbitrary laminar flow field, and subjected only to aerodynamic drag, gravitational forces, and inertial forces. The particle density is much larger than the air density, so the buoyancy forces can be neglected. The fluid velocity relative to the XYZ-system of coordinates fixed to the ground is \((u', v', w')\), and the particle velocity relative to the ground is \((u, v, w)\). The Z-axis is positive upward, so that the gravitational acceleration \( g \) points in the negative Z-direction.

The components of the particle velocity relative to the moving air are: \((u-u')\), \((v-v')\), and \((w-w')\), and the magnitude of the velocity is:

\[
V_p = (u-u')^2 + (v-v')^2 + (w-w')^2
\]  

Hence the magnitude of the particle drag is:

\[
D_p = C_D \frac{1}{2} \rho V_p^2 A_p
\]

where \( C_D \) = drag coefficient, and \( A_p \) = frontal area. In case of spheres the drag can be written:

\[
D_p = k V_p^2
\]

where:

\[
k = \frac{1}{8} C_D \rho \pi d_p^2
\]

The three drag components have the magnitudes:

\[
\begin{align*}
D_{px} &= D_p \frac{u-u'}{V_p} = k(u-u') V_p \\
D_{py} &= D_p \frac{v-v'}{V_p} = k(v-v') V_p \\
D_{pz} &= D_p \frac{w-w'}{V_p} = k(w-w') V_p
\end{align*}
\]

Equilibrium of drag, gravitational forces and inertial forces then yields the equations of motion:
\[
\frac{du}{dt} = - \frac{k}{m} (u-u') \frac{V}{p} \\
\frac{dv}{dt} = - \frac{k}{m} (v-v') \frac{V}{p} \quad (6a) \\
\frac{dw}{dt} = - \frac{k}{m} (w-w') \frac{V}{p} - g
\]

and:
\[
\alpha = \frac{dx}{dt} ; \quad \beta = \frac{dy}{dt} ; \quad \gamma = \frac{dz}{dt} \quad (6b)
\]

Equations 6 are the basic equations of motion of a particle falling in an arbitrary laminar flow. In order to non-dimensionalize these equations, so that they are valid in all dimensional systems, the distances are divided by the characteristic length \(L\), the speeds by the characteristic velocity \(V\) (either jet or wind), and time by \(t* = L/V\). The non-dimensional quantities are identified by the "hat" symbol \(\hat{\cdot}\). The result is:

\[
\frac{\hat{u}}{\hat{\alpha}} = - \frac{kL}{m} (\hat{u}-\hat{u}') \frac{\hat{\alpha}}{V} \\
\frac{\hat{v}}{\hat{\alpha}} = - \frac{kL}{m} (\hat{v}-\hat{v}') \frac{\hat{\alpha}}{V} \\
\frac{\hat{w}}{\hat{\alpha}} = - \frac{kL}{m} (\hat{w}-\hat{w}') \frac{\hat{\alpha}}{V} - \frac{gL}{V^2} \quad (7a)
\]

and:
\[
\hat{\alpha} = \frac{\hat{u}}{\hat{\alpha}} ; \quad \hat{\beta} = \frac{\hat{v}}{\hat{\alpha}} ; \quad \hat{\gamma} = \frac{\hat{w}}{\hat{\alpha}} \quad (7b)
\]

In these equations there appear to be only two non-dimensional groups:

\[
\Pi_1 = \frac{kL}{m} \quad (8)
\]

\[
\Pi_2 = \frac{gL}{V^2} \quad \text{(has form of Froude number)}
\]

instead of the six groups found when using the \(\pi\)-theorem. The groups \(\Pi_1\) and \(\Pi_2\) apparently combine four of the six \(\pi\) - groups, because:

\[
\Pi_1 = \frac{1/8C_D \rho \pi d_p^2}{1/6 \pi d_p^3 \rho_p} = \frac{3}{4} \frac{C_D}{\rho_p \frac{L}{d_p}} \frac{1}{\frac{L}{d_p}} = \frac{3}{4} C_D \pi_1 \frac{1}{\pi_4} \quad (9)
\]
(where $C_D$ is a function of Reynolds number, i.e., of $\pi_5$), and:

$$\Pi_2 = \frac{1}{\eta_6}$$  \hspace{1cm} (10)

Still another simplification can be found by manipulating $\Pi_1$ so that $\Pi_2$ can be expressed as a function of $\Pi_1$. Equation 3 shows the drag of a particle moving at velocity $V$ to be $kV^2$. Hence, when falling in still air at terminal velocity $V_t$ the particle drag is $kV_t^2$ and equilibrium between weight and drag yields:

$$mg = kV_t^2$$

or:

$$k = \frac{mg}{V_t^2}$$

so that:

$$\Pi_1 = \frac{kL}{m} = \frac{gL^2}{V_t^2} = \Pi_2 \left(\frac{V}{V_t}\right)^2$$

and:

$$\Pi_2 = \Pi_1 \left(\frac{V_t}{V}\right)^2$$  \hspace{1cm} (11)

Hence the non-dimensional equations of motion 7 can be rewritten in their final form:

$$\frac{d\hat{u}}{dt} = -\Pi_1 (\hat{u} - \hat{u}') \hat{V}_p$$

$$\frac{d\hat{v}}{dt} = -\Pi_1 (\hat{v} - \hat{v}') \hat{V}_p$$  \hspace{1cm} (12a)

$$\frac{d\hat{w}}{dt} = -\Pi_1 \left\{ (\hat{w} - \hat{w}') \hat{V}_p + \left(\frac{V_t}{V}\right)^2 \right\}$$

and:

$$\hat{u} = \frac{dx}{dt}; \hspace{0.5cm} \hat{v} = \frac{dy}{dt}; \hspace{0.5cm} \hat{w} = \frac{dz}{dt}$$  \hspace{1cm} (12b)

where:

$$\Pi_1 = \frac{kL}{m} = \frac{3}{4} C_D \frac{\rho_p}{\rho} \frac{L}{d_p}$$

Hence, full scale and model experiments will yield dynamically similar results if the following modelling laws are satisfied:
1) \[ \Pi_1 = \frac{3}{4} C_D \frac{\rho}{\rho_p} \frac{L}{d_p} = \text{CONSTANT} \]

2) \[ \frac{V_t}{V} = \text{CONSTANT} \quad (13) \]

3) \[ \hat{u}', \hat{v}', \text{and} \hat{w}' \text{ are fixed functions of } \hat{x}, \hat{y} \text{ and } \hat{z}. \]

The first condition shows that the single parameter \( \Pi_1 \) combines several effects. The particle drag coefficient, the density ratio, and the size ratio do not need to be modelled separately as required by the pi-theorem, but only in combination, which is of course considerably more convenient.

As \[ \Pi_1 = \Pi_2 \left( \frac{V}{V_t} \right)^2 = \frac{gL}{V_t^2} \]

it also follows from this condition that \( V_t \) must be proportional to \( \sqrt{L} \).

The second condition requires the flow velocity \( V \) to be scaled with the particle terminal velocity \( V_t \) and hence also with \( \sqrt{L} \).

The third condition requires kinematic similarity between the full scale and model flow fields, which condition is effectively met if the geometries are similar and if the jet velocities are proportional to the wind velocity.

The modelling problem in this simplified but quite useful particle-flow interaction system then reduces to finding particles of the correct size and weight to possess the terminal velocity required by the condition \( \Pi_1 = \text{constant} \) (i.e., \( V_t \propto \sqrt{L} \)), and then to scale the wind and jet velocities proportionally. The time model scale is found as the ratio of geometric and velocity scales.

II.3 Selection of tunnel and model characteristics

A tunnel with a 16 ft. long test section having a cross section of 3-1/2 ft. by 3-1/2 ft. is about the maximum size tunnel that can be fitted into the available space. These dimensions seem to justify the use of building models with a characteristic length of maximum 1 ft., which leads for example to the choice of a linear geometric model scale of 1: 100 for a 100 ft. building. It follows then from the scaling laws derived in the previous section that the velocity scale factor and the time scale factor are both 1: 10 for this case. All model velocities must therefore be 1/10th of the corresponding full scale velocities. If a maximum full scale wind velocity of 100 ft/sec is chosen to be modelled in the tunnel, the maximum tunnel flow velocity then must be 10 ft/sec. The corresponding Reynolds number per foot characteristic length is 64000.

The material and size of the simulation particles are selected by studying the terminal velocities of precipitation, see the Appendix. If a terminal velocity range \( 1 \leq V_t \leq 30 \text{ ft/sec} \) is desired to be simulated, covering most raindrop and snow particle sizes (see Figs. A4,5,6 of the Appendix), then the terminal velocity range of the simulation particles should be \( 0.1 \leq V_t \leq 3 \text{ ft/sec} \).
Various materials for simulating rain and snow have been mentioned in the literature, ranging from sawdust in a wind tunnel to mercury drops in a water tunnel (see the references mentioned in Section A.1.4 of the Appendix). A number of these materials can be employed in the Precipitation Wind Tunnel, and a study of their applicability to specific research projects should be undertaken. However, the most convenient particles to be used in the present early stages of research on precipitation simulation appear to be small spherical glass beads. Relevant data on physical properties and terminal velocities of commercially available glass beads of predominantly spherical shape are presented in Section VII. Some investigations on the behaviour of small glass beads are described in Refs. 5, 27, 28, 30, 35.

Hence, the particles selected to simulate precipitation are spherical glass beads of specific gravity 2.4, having a terminal velocity range $0.1 \leq V_t \leq 3$ ft/sec. The relationship between bead terminal velocity and diameter, determined in Section VII.2, is presented in Fig. 13. It follows from this curve that the glass beads selected to simulate rain and snow should have a diameter range $20 \leq d_p \leq 150 \mu m$. The particle size range occurring in an actual rain or snow shower is then simulated by means of the corresponding bead size range selected from Figs. A.4 and A.5 (snow), A.6 (rain), and 13 (beads). Ideally the size distributions in each size range should correspond to those of the precipitate particles (see Refs. 13, 33, 34, 57, 58).

II.4 Main features of tunnel circuit

The tunnel has been designed with the requirements of Section II.1 in mind. In addition to other references mentioned throughout this report, much useful information has been obtained from the following publications on low speed wind tunnels: Refs. 6, 7, 14, 19, 22, 49, 51, 53, 54.

The tunnel is placed along one wall of a large laboratory room, occupying a space of about 8.5 ft x 10.5 ft x 46 ft. It is a closed circuit, closed test section configuration, and consists of three basic units: tunnel duct, drive, and return duct: see Figs. 1 and 2. The closed configuration renders the tunnel flow completely insensitive to outside disturbances such as people walking by, etc., in spite of the very low energy level of the air stream. Most of the noise generated by the fan and the moving air remains inside the closed circuit, so that the outside noise level is low enough not to bother the tunnel operator.

The tunnel duct has a total length of about 32.5 ft. and is constructed from 1/2 in. (front and back panels) and 3/4 in. (roof and floor panels) plywood sheets, supported by slotted angle iron posts and frames. There are no curved construction elements and all the parts are assembled by means of bolts and nuts and wood screws. The largest elements are three vertical support frames, measuring about 7.5 ft. x 9.5 ft. x 0.5 ft., and welded together from slotted angle iron posts. Sponge rubber strips 1/8 in. thick are used wherever leaking away of tunnel air and/or glass beads must be prevented.

The tunnel duct, which does not have a contraction, has inside dimensions 3-1/2 ft. x 3-1/2 ft., and is made up of four independently built sections, i.e., the screen, profile, test, and end sections. The screen section is about 1-1/2 ft. long and consists of a four-sided diffuser with a total included angle of about 34°, and a 2 ft. long straight part following the diffuser. Seven screens
are built into the screen section to ensure proper velocity and turbulence characteristics of the flow in the empty tunnel. The 6 ft. long profile section can be used to install apparatus for the generation of required velocity profiles and turbulence intensities. The test section, in which the model structures are installed, is 16 ft. long and has a transparent front panel for observing the flow. The last section of the tunnel duct is the 6 ft. long end section in which air filters, lights, cameras, etc., can be installed.

The tunnel duct interior, which is painted mat black, is readily accessible through five large hatches in the back panels of the profile, test, and end sections, (see Fig.3). Another large hatch is located in the floor of the test section.

The glass beads used to simulate the precipitation are introduced into the tunnel airstream by means of a bead feed system employing a bead feed box with vibrating sieves, located at one of five positions on the tunnel roof.

The tunnel air is circulated through the circuit by means of a 21 in. diameter axial flow fan driven by a three horse power electric motor. The fan rpm can be accurately set at any desired value by means of an electro-mechanical remote control system.

The return duct is a 2 ft. inside diameter sheetmetal tube supported by slotted angle iron poles. The plane of the return duct is set at about 45° to the vertical plane through the tunnel duct axis, in order to fully utilize the available space. This leaves all four sides of the tunnel duct free for easy access and installation of apparatus.

III. DESCRIPTIONS OF TUNNEL COMPONENTS

III.1 Drive

The three horse power U.S. Varidrive Motor (type VA-TF, Frame 15-182T) consists of a constant speed NuRate motor (type TEFC, 575 volts, 3 phase), and a continuously variable speed control mechanism. The stepless change of the rotational speed of the drive axis is achieved by simultaneously changing the effective diameters of a set of pulleys over which a heavy duty deep cog belt is running; see Fig.4. A simple high-low push button station at the tunnel control table sets the pulley diameters at the desired ratio by means of a Type ERR electro-mechanical remote control unit, in which a small 115 volt motor drives a lever system connected to the spring-loaded pulley-discs. The speed of the drive axis can be accurately set at any desired value within the range 450 to 450 rpm.

The Varidrive Motor is mounted on a small platform on top of the 26.5 in. long steel duct which contains the 7-blade aluminum axial flow fan, driven by the motor via two standard belts.

The 21 in. diameter Vaneaxial fan Type MB, supplied by the Canadian Blower and Forge Company Ltd., is rated at a maximum volume flow of 7350 cfm at 2300 rpm and a total pressure difference of 2.15 in. water. Transition from the 21 in. diameter fan housing to the 24 in. diameter return duct is achieved by means of a 9.5 in. long steel diffuser. Flexible sleeves of 1/8 in. thick rubber between tunnel end section and fan housing inlet, and between fan housing diffuser and return duct, effectively block transmission of the small-scale vibrations generated by the drive unit. The 4 ft. high table on which the drive unit is
mounted is constructed from slotted angle iron and heavy plywood, and supplies a stable support for the motor-fan assembly.

A push button station located at the tunnel control table is used for starting and stopping the motor. A schematic of the electrical wiring diagram of the tunnel drive system is given in Fig. 5.

III.2 Return duct

The 2 ft. inside diameter duct was made by a commercial sheet-metal company from 20 gauge galvanized sheet iron. It consists of a number of straight 3 ft. long sections and four 90° corners (elbows), fastened to each other by means of sheet metal screws and then sealed airtight with duct-sealing tape. The corners do not contain guide vanes.

The total length of the duct center line is about 59.5 ft., and the four corners (multi-jointed mitre bends) have a centre line radius of 2 ft. The 3 ft. long section located about 8 ft. in front of the third corner supports the double venturi static tube and the pitot tube used for monitoring the test section wind velocity, see Section V. The return duct is connected to the screen section through a 1/8 in. thick rubber sleeve.

III.3 Screen section

Because of space limitations, the transition from the 2 ft. diameter return duct to the 3-1/2 ft. by 3-1/2 ft. cross section of the tunnel duct should take place over as short a distance as possible. This implies the use of a wide-angle diffuser, instead of a conventional one with a maximum total included angle of only about 10°. The flow separation problems in wide-angle diffusers having a total angle of up to about 45° can largely be overcome by using special devices such as vanes, splitter plates, spoilers, rods, screens, etc., see Refs. 12, 41, 45, 55, 56, 59.

As the low efficiency of such modified wide-angle diffusers is of no concern in the present design, it was decided to employ a 2.5 ft. long diffuser shaped like a four-sided truncated pyramid, having a total included angle between opposing sides of 34°, and an expansion ratio of inlet and outlet areas of 1: 3.9. (This ratio is equal to that of a conical diffuser of the same length having a total included angle of 42°). Four separation-preventing screen are mounted in the diffuser at a distance of 8 in. from each other, and three more screens are installed in the 2 ft. long straight part of 3-1/2 ft. by 3-1/2 ft. cross section following the diffuser.

The seven screens are made from 0.0105 in. diameter round aluminum wire and have a mesh value of 17 (i.e., number of wires per inch), giving a solidity of 0.357. The screens are attached to and supported by narrow steel frames bolted to the side walls, roof, and floor of the screen section. Four side panels, two on each side, can be removed for inspection and cleaning of the screens. A photograph of the screen section with two side panels removed, showing six of the seven screens, is presented in Fig. 6.

III.4 Profile section

This 6 ft. long section is incorporated in the tunnel design in order to be able to generate as accurately as possible certain required velocity profiles.
and turbulence intensities of the test section flow. This can be achieved by means of one or more of various well-known methods employing blocks, spires, rods, screens, barriers, vortex generators, surface roughness, etc., see Refs. 4, 15, 17, 19, 40, 43. The profiles generated by using such techniques in the relatively short duct of the present tunnel are expected to be reasonably useful approximations of the desired distributions. The best results would be obtained by means of a very long tunnel duct.

III.5 Test section

The 15 ft. 8 in. x 3-1/2 ft. front panel of this 16 ft. long section is constructed from 1/2 in. transparent Plexiglas, making uninterrupted observation of the flow possible. A 2.3 ft. by 6 ft. removable hatch in the floor enables easy installation of building models. General illumination of the test section interior is provided by four removable lighting units in the tunnel roof, using a number of ordinary 100 W bulbs. The bead feed box used for introducing glass beads into the tunnel flow (see Section VII.3) can be placed at 5 different locations on the roof of the test and profile sections, see Fig. 2.

III.6 End section

Because of design simplicity and lack of interest in power efficiency, the transition from the 3-1/2 ft. tunnel cross section to the 21 in. diameter fan housing inlet is not achieved by means of a gradual contraction, but rather by an abrupt change in cross section at the end panel of the tunnel duct. The accompanying curvature of the streamlines approaching the 21 in. diameter outlet hole in the end panel should not extend upstream into the test section, and therefore the 6 ft. long end section is placed between the test section and the end panel.

A dust filter made from sheets of fine cotton wool, foam rubber, etc., to filter very fine suspended glass particles out of the air, can be mounted on a slotted angle iron support frame bolted to the four walls about 2 ft. in front of the end panel.

IV. ENERGY RATIO AND POWER REQUIREMENTS

Expansion, turbulent mixing, skin friction, etc. lead to loss of flow energy through heat dissipation, evidenced by a drop in pressure along the tunnel duct. These losses must be compensated for by introducing energy into the air stream in the form of a static pressure rise supplied by the axial flow fan. Air leaking out through wall openings should also be replaced.

The method used in this design study to calculate the maximum power required to compensate for the losses is the conventional one proposed in Ref. 63, see also Refs. 49, 53, 54. The tunnel circuit, less fan and motor, is broken down into a number of components: cylindrical sections, corners, diffusers, and screens. The pressure losses are calculated separately for each component by using standard methods and empirical data. The overall circuit loss is then found by summation of the component losses. It is supposed that no air is leaking out of the circuit.

The energy loss in each component is presented in the form of a loss parameter, defined as the static pressure drop Δp across the component, referred to the dynamic pressure q_o of the test section flow:
\[ K_o = \frac{\Delta p}{q_o} \]  \hspace{1cm} (14)

Hence the power loss in the component is \( \Delta p \) \( q_o \) \( Q_o \) where \( Q_o \) = test section volume flow. The total tunnel loss coefficient is

\[ \Sigma K_o \]

and the total power loss is:

\[ \Sigma K_o q_o Q_o \] \hspace{1cm} (15)

The tunnel efficiency is usually expressed in a different coefficient form by defining the tunnel energy ratio:

\[ ER_t = \frac{\text{kinetic energy per second in test section flow}}{\text{power input into flow at fan (equals sum of losses)}} \] \hspace{1cm} (16)

Hence the tunnel efficiency increases with increasing energy ratio.

Now:

\[ ER_t = \frac{q_o Q_o}{\Sigma K_o q_o Q_o} = \frac{1}{\Sigma K_o} \] \hspace{1cm} (17)

where: \( \eta_f \) = fan efficiency,

and: \( \text{BHP} \) = motor brake horsepower supplied to fan.

It follows from Equations 15 and 16 that:

\[ ER_t = \frac{q_o Q_o}{\Sigma K_o q_o Q_o} = \frac{1}{\Sigma K_o} \] \hspace{1cm} (18)

and hence from Equations 17 and 18:

\[ \text{BHP} = \frac{q_o Q_o}{550 \cdot \eta_f \cdot \Sigma K_o} \] \hspace{1cm} (19)

where:

\[ q_o Q_o = \frac{1}{2} \rho V_o^3 A_o \]

and:

\[ K_o = \frac{\Delta p}{q_o} = \frac{\Delta p}{\frac{1}{2} \rho V_o^2} \]

giving the required motor horsepower.

The approximate loss coefficients of the present tunnel components, calculated for \( V_o = 10 \text{ ft/sec} \), and using methods and data from Refs. 2, 49, 53, are:
The total tunnel loss coefficient has a value of 75 (and hence $E_{t} = 0.0133$), which is very high compared to those of conventional closed circuit low speed wind tunnels, where values between 0.1 and 2 are usually found.

From Equation 19 and by taking $\eta = 0.70$, the required motor horse-power of the empty tunnel is found to be about 2.9 hp, so that a 3 hp motor is more than sufficient to drive the tunnel.

V. SPEED SETTING

Because of the low air velocity ($V_o < 10$ ft/sec), the energy level of the test section flow is very low ($q_o < 0.023$ in., i.e., 0.59 mm water), so that measuring these velocities with reasonably simple instrumentation poses quite a problem. In order to find a useful solution, the following special low-velocity measuring methods have been studied:

a) pitot-static tubes connected to liquid micro-manometers, Refs. 9, 20, 48, 49;

b) miscellaneous manometers used in vacuum technique, Refs. 21, 23;

c) mechanical and electro-mechanical transducers, Refs. 10, 20, 21, 23;

d) hotwire and thermistor techniques, Refs. 1, 20, 42;

e) hotwire measurement of the shedding frequency of vortices in the wake of circular cylinders, Ref. 32;

f) fluidic velocity sensor, presenting the air velocity as a function of the deflection of a turbulent jet normal to the measured flow, Ref. 62;

g) pendulum anemometer made from a standard table tennis ball suspended from a thin wire, the deflection of which is a measure of the air velocity, Ref. 16;

h) directly timing the velocity of neutrally buoyant particles suspended in the air flow, such as smoke puffs and helium-filled soap bubbles.

Although these methods are generally useful in measuring low velocities or pressures, their applicability in the Precipitation Wind Tunnel appears to be limited, because they all possess one or more of various disadvantages such as

<table>
<thead>
<tr>
<th>Component</th>
<th>$K_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>tunnel duct</td>
<td>negligible</td>
</tr>
<tr>
<td>straight parts of return duct</td>
<td>5</td>
</tr>
<tr>
<td>corners</td>
<td>17</td>
</tr>
<tr>
<td>diffuser (zero efficiency)</td>
<td>15</td>
</tr>
<tr>
<td>screens</td>
<td>13</td>
</tr>
<tr>
<td>unknown (leaks, joints, extra screens, double venturi in return duct, etc.)</td>
<td>25</td>
</tr>
</tbody>
</table>
as: too complicated, too large, not sturdy enough, expensive, not accurate enough, unstable, need frequent calibration, awkward to use, etc. Another method of monitoring the test section air speed must obviously be found.

It was therefore decided to make use of the unorthodox tunnel geometry and place a specially designed pressure sensing probe, composed of a venturi-shaped static pressure tube and a conventional pitot tube, in the return duct. The mean velocity in this duct is about four times higher than that in the test section, and the static pressure is correspondingly lower. By taking the static pressure at the throat of the venturi-shaped static tube, a static pressure is then obtained that is not only lower than the static pressure in the undisturbed return duct flow, but also much lower than the static pressure in the test section, because of the combined effects of return duct velocity and venturi-shaped static tube. An even lower static pressure can be obtained by using a double venturi static tube, i.e., a venturi placed inside the entrance cone of a larger venturi.

The difference between the static pressure in the venturi throat, and the total pressure in the return duct measured by means of the pitot tube, is therefore not only many times larger than the corresponding mean dynamic pressure of the test section flow, but it also has a fixed relation to this dynamic pressure, based upon the area ratio of test section and return duct cross sections and the dimensions of the venturi. When the "augmented" pressure difference measured in the return duct is then connected to a conventional Betz manometer, an accurate, convenient, and cheap method is found to directly monitor the mean test section speed. As long as the area ratio remains constant, a single calibration is sufficient to establish the relationship between this speed and the manometer indication.

The double venturi static tube used in the present tunnel is composed of a small, brass, cylindrical venturi, mounted by means of two thin support plates inside the entrance cone of a large, aluminum, streamline-shaped venturi, see Figs. 7 and 8. The dimensions of the instrument are about 2/3 of those given in Ref. 8, see also Ref. 60. It is supported by means of six steel rods along the centre line of the 3 ft. long duct section located about 8 ft. from the third corner. This section is secured to the rest of the return duct by means of two large clamps, and it can easily be removed for inspection and maintenance. The static pressure at the throat of the small venturi is led through a hollow support rod to the outside of the return duct. The total pressure in the pitot tube mounted on one of the other support rods is also led to the outside of the duct. Plastic tubing is used to feed both pressures into the Betz manometer at the tunnel control table.

The performance of the double venturi static pitot tube instrument has been investigated by placing it, with the six support rods but without the return duct section, in the 32 in. by 48 in. test section of the UTIAS Subsonic Wind Tunnel, and measuring the indicated pressure difference $\Delta p_{dv}$ as a function of the tunnel velocity $V_{st}$ up to about 40 ft./sec. The results of these measurements are presented in Fig. 9, together with the corresponding tunnel dynamic pressure $q_{st}$. A marked augmentation of $\Delta p_{dv}$ over $q_{st}$ is evident from these curves.

However, the streamlined outer shape of the large venturi appears to give rise to unsatisfactory performance of the double venturi static pressure probe.
the static pressure in the small throat is unsteady and it is not as low as expected. Apparently the flow in the wake behind the large venturi, which directly influences the flow through the venturis and hence the throat static pressure, is not steady and the wake pressure is too high. Irregular separation and shedding of vortices from the streamlined aft portion of the large venturi must be blamed for these phenomena.

This problem was successfully remedied by installing a number of 0.5 in. wide and 2.5 in. long aluminum strip spoilers along the circumference of the aft portion of the large venturi, at an angle of about 60° to the venturi axis, see Fig. 7. The wake conditions were now much improved: the unsteadiness practically disappeared and \( \Delta p_{dv} \) was considerably larger than in case of the smooth streamline shape, see Fig. 9. The augmentation factor \( \Delta p_{dv}/q_{st} \) ranges from about 7 at \( V_{st} = 4 \) ft/sec to about 16.3 at \( V_{st} = 40 \) ft/sec.

By placing the double venturi - pitot tube instrument in the return duct of the Precipitation Wind Tunnel, the relationship between \( \Delta p_{dv} \), indicated by the Betz manometer, and the mean test section velocity \( V_o \), measured by timing smoke puffs in the tunnel duct, can be established. The results presented in Fig. 10 indicate an augmentation factor \( \Delta p_{dv}/q_{o} \) of about 53 at \( V_o = 1 \) ft/sec, and about 285 at 10 ft/sec. Figure 10 is then used for setting the speed of the empty tunnel at any desired value up to 10 ft/sec. At the higher values of \( \Delta p_{dv} \) some unsteadiness is present in the manometer indication, probably caused by separation and rotation of the return duct flow, induced by the first and second corners. The flow quality can be improved by mounting screens in the return duct behind the second corner.

VI. CALIBRATION OF TEST SECTION FLOW

Hotwire measurements have been performed to investigate some properties of the flow in the central cross section of the tunnel, i.e., 8 ft. from the beginning of the test section. The results of velocity measurements in 25 points of this cross section are presented in Fig. 11 for three tunnel speeds \( V_o = 1, 4, \) and 9 ft/sec. Except for the flow near the walls, the velocity distribution appears to be reasonably flat with maximum deviations of about \( \pm 3\% \) of \( V_o \).

The turbulence intensities of the longitudinal velocity component in this area of the cross section are about \( 0.3\% \) and \( 1\% \) at \( V_o = 4 \) and 9 ft/sec respectively.

Visual observation of smoke streaks at the lower tunnel velocities did not indicate the presence of flow rotation.

VII. GLASS BEADS

VII.1 Physical properties

The glass beads selected to simulate the precipitate particles (see Section II.3) are supplied by the Microbeads Division of the Cataphote Corporation, Toledo, Ohio. Some of the technical data presented by the supplier are the following:
-- manufactured from high-grade optical crown glass;

-- specific gravity of solid glass relative to water at 4°C is 2.5; that of the beads ranges from 2.4 to 2.5 with the smaller values in the finer bead sizes;

-- predominantly spherical in shape, containing not more than 5% irregularly shaped particles;

-- available in 19 size ranges between 1 μm and 840 μm, and guaranteed 90% in the range specified; (size distributions in each size range are not given);

-- completely waterproofed by application of a permanent molecular film of silicone material to the outer surfaces.

Of the several methods available for size grading of the beads (Refs. 11,18,38,39,47), the easiest and most rapid one is mechanical sieving using standard sieves made from precision woven wire cloth.

Beads in three different size ranges have been selected for further study and use in the wind tunnel:

<table>
<thead>
<tr>
<th>number</th>
<th>size range</th>
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<tbody>
<tr>
<td>812</td>
<td>177 - 124 μm</td>
</tr>
<tr>
<td>1420</td>
<td>105 - 74 μm</td>
</tr>
<tr>
<td>2740</td>
<td>53 - 28 μm</td>
</tr>
</tbody>
</table>

The specific gravity of these small beads is supposed to be 2.4. The number 812 and 1420 beads are free flowing and can easily be poured out of a container, whereas the number 2740 beads are not free flowing.

Microphotographs (100X) of beads in these three size ranges, presented in Fig. 12, show that most beads are indeed spherical in shape with a smooth surface, but that small imperfections such as bubbles and protrusions are quite common.

VII.2 Terminal velocity

The scaling laws discussed in Section II.2 show that the terminal velocity is a most important property of the beads, next to size, shape, and specific gravity. The terminal velocity mentioned in that section is that of an individual particle falling freely in unbounded still air, not influenced by the proximity of other particles. There is, however, some indication that particle interaction can have considerable influence on the terminal velocity of particles falling together, the size and concentration of the particles being the main parameters (see the Notes in Sections A.2.2 and A.2.4 of the Appendix). This effect has also been noted during some tentative experiments with glass beads in the present wind tunnel and in a 9-1/2 ft. long vertical drop-test tube. The terminal velocity of the beads seems to increase with increasing concentration, but no quantitative results have as yet been obtained.
Obviously a technique is needed to accurately measure the terminal velocity of an individual particle, falling either alone or in the company of other particles in different concentrations. Such investigations should also be performed on real precipitation to determine whether its concentration has any influence on the terminal velocity of individual precipitate particles. If proximity effects are indeed significant, it might be necessary to incorporate them in the model experiments.

As such a technique for measuring the terminal velocities of individual particles falling in groups is not yet available, the terminal velocity of the glass beads used in this design study is defined as that of an individual, smooth, spherical particle of specific gravity 2.4, falling alone in unbounded air, and calculated by means of the method discussed in Section A.2.2 of the Appendix. The results of calculations of beads in the size range $10 < d < 1000 \, \mu m$ are presented in Fig. 13.

VII.3 Bead feed system

The glass beads are introduced into the tunnel air stream by means of a bead feed box which can be bolted to the tunnel roof in five different positions, see Fig. 2. The box is made from $3/4$ in. plywood and consists of a 20 in. by 31 in. outer frame which supports, by means of small foam plastic cushions in the four corners, a board containing three standard 8 in. diameter sieves, see Fig. 14. The board and the sieves are vibrated by means of a small 115 volt commercial massage vibrator mounted in the centre of the board and controlled by means of a variable transformer at the tunnel control table. A 1 in. thick lightweight paper honeycomb with $1/8$ in. diameter cells is mounted on top of the wirecloth of each sieve to prevent movement and spreading of the beads over the wirecloth. The bead flow into the tunnel air stream is a function of the bead size, the dimensions of the sieve openings, the distribution of the beads in the honeycombs, and the rotational speed of the vibrator motor.
APPENDIX A: PRECIPITATION AERODYNAMICS

A.1 General Review

A.1.1 Full-scale investigations

The physical properties of the atmospheric particles rain, snow, and hail, have over the years been investigated to a considerable extent, mainly from a meteorological point of view. In Ref. A58 a comprehensive survey on the physics of natural precipitation processes is presented, and discussions on the general properties of snow are given in Refs. 33, A58, A60, A61. An invaluable source of information on snow and hail is Ref. A1.

The aerodynamic behaviour of freely moving atmospheric particles is extremely complicated because it concerns three-dimensional turbulent flows of air with fluid and/or solid particles which are characterized by various complex properties such as: drop collision and coalescence (Refs. A17, A56, A58, A63), drop deformation (Refs. A41, A49, A58, A59, A72, A74, A78, A81, A84), drop internal circulation (Refs. A53, A72, A78), drop evaporation (Refs. A8, A17, A22, A77, A84), drop break-up (Refs. 31, A12, A14, A20, A27, A42, A49, A58), snow crystal shapes (Refs. 33, A9, A17, A48, A58, A60), hail stone shapes (Ref. A58).

Of the many problems in full-scale precipitation aerodynamics, only two have received a reasonable amount of attention: i) the relatively simple one-dimensional flow phenomenon of particles falling freely at terminal velocity in still air (to be reviewed in Section A.2), and ii) blowing or drifting of snow.

Blowing of snow can take place when the snow lying on the ground is dry and the wind velocity is higher than about 10mph. Drifts form when snow-bearing winds meet obstacles which cause eddies in the wind stream and a local reduction in wind speed. The snow is deposited out of the wind stream into these regions of comparative calm, and the process continues for as long as an obstacle is effective in reducing the wind speed (Ref. A75). When blown by strong winds, snow crystals are broken and abraded into roughly equidimensional grains with rounded or subangular corners. Particles occur in greatest number in the size range 20 to 400 μm (Ref. 44). Full-scale measurements and analyses of blowing snow have been reported in for instance Refs. 33, A6, A15, A16, A19, A62, A66, A80. A comprehensive review on blowing snow is presented in Ref. 44.

The drifting or blowing of snow is an example of the general phenomenon of transportation of solid particles by a fluid moving over a surface composed of such particles. It is characterized by the existence of two kinds of new particles carried by the wind: particles supplied directly from precipitation, and particles deposited on the ground surface earlier and then subsequently picked up by the wind. The three transport mechanisms which have been distinguished are (Ref. 44): creep (the particles roll and skid over the surface while still in contact with the surface most of the time), saltation (the particles bound along the surface travelling a curved trajectory under the influence of wind and gravity forces), and turbulent diffusion (the particles are held in suspension by vertical mixing, so that they travel in the air stream without necessarily contacting the ground). There is in many ways a marked similarity between blowing snow and blowing sand (Ref. A5).
The accumulations of snow blowing across surfaces and around obstacles have characteristic shapes called ripples, dunes, waves, sastrugi, barchans. These are determined by factors such as shape of the ground surface, shape and orientation of the obstructing barrier, properties of the wind (velocity, direction, profile, turbulence), properties of the snow particles, etc. (Refs. 44, A18, A21, A26, A66). The formation of unwanted snow accumulations can be avoided with varying degrees of efficiency by i) correct design and orientation of the obstacles concerned, ii) putting up natural barriers such as trees, weed, shrub, earth banks, etc., and iii) putting up artificial barriers such as snow fences of correct design and location (Refs. 44, A26, A28, A33, A47, A75).

A.1.2 Need for model research

Although the terminal velocities of freely falling particles and the properties of blowing snow have been investigated to some extent, a marked lack of knowledge exists of other phenomena in precipitation aerodynamics. An example of the complex flows concerned is the three-dimensional flow field of particles suspended in turbulent air moving around irregularly shaped obstacles such as buildings, towers, fences, trees, etc., placed upon the ground. An even more complicated flow field exists when the wind-particle mixture interacts with an air jet issuing at some angle into the wind. Such air jets are increasingly being used as screens, curtains, doors, enclosures, for protection of a portion of space.

One can even conceive of a building with no solid structure at all, i.e., using the air screens as a total structural envelope. These so-called "dynamic structures" can have variable form and "strength"; they are characterized by the expenditure of energy rather than by the utilization of mass as in conventional static structures (Refs. 25, 26, 29). An example of the dynamic structure concept is the annular air-curtain roof or air dome, which forms because of the coalescence of an upwardly directed annular jet (Refs. 25, 37). A fundamental problem in the development of dynamic structures is the extent to which they can provide protection against the penetration of atmospheric particles.

Considerable research is needed before sufficient knowledge will have been assembled on the three-dimensional flows mentioned above. Besides full-scale research, obviously difficult to perform, mathematical as well as experimental models must be used to develop adequate methods for predicting trajectories, diffusion, distribution, etc., of the particles.

The present state-of-the-art of mathematical and experimental model research on precipitation aerodynamics will now be briefly reviewed.

A.1.3 Mathematical models

The trajectories of particles of arbitrary shape moving in a fluid can in principle be found by solving the general equations of motion of the particle (Ref. A37) with respect to the appropriate boundary conditions of particle, fluid and container. However, because of the exceedingly complex flow fields and the non-linearity of the equations, the solutions cannot be obtained in explicit form. More or less far-reaching simplifications must therefore be introduced in order to be able to find useful solutions to the problem. A large amount of information has thus been acquired on the dynamics of particles, and many publications are available on general and specific theoretical problems (see for instance Refs. 18, 33, 39, A13, A14, A36, A37, A38, A41, A45, A51, A57, A64, A65, A68, A79, A82, A85). Much of this knowledge is of course also relevent to the special
case of precipitation aerodynamics.

Publications specifically on theoretical precipitation aerodynamics are rare; they are almost exclusively concerned with terminal velocity (see Section A.2) and blowing snow. Studies on the theoretical mechanics of blowing particles (snow and sand) are presented in Refs. 33,61,A15,A16,A19,A23,A24,A33,A62,A69. A subject that has received some attention because of its connection with the formation of ice on aircraft is the deposition of drops on obstacles from a moving stream. Methods to calculate two-dimensional trajectories of drops moving around cylindrical obstacles are discussed in Refs. A10,A32,A49,A76.

At the Institute for Aerospace Studies a method has been developed to solve the equation of motion of solid spheres, falling into a plane laminar jet issuing into a normal laminar crosswind, by means of numerical machine computation techniques (Refs.3,24). The computed particle trajectories in this two-dimensional flow problem appear to fall roughly into two categories denoted "in-jet" (i.e., the jet momentum influences the particle path for a substantial portion of its travel), and "ballistic" (i.e., the jet provides a brief impulse which launches the particle into the calm wake region downstream of the jet exit).

Numerical calculations of particle trajectories in a two-dimensional two-phase flow field (particles falling vertically into a laminar jet issuing horizontally in still air), where attention was also paid to drop deformation and break-up, are presented in Refs. 25,31.

One may conclude from these computational investigations that a quantitative knowledge of the detailed structure of the jet flow would permit the calculation of drop trajectories entirely from theory. Experiments could then be conducted numerically on a computer. The large number of parameters involved in physical experiments may make the computer technique very useful as an alternative (Ref.37).

A.1.4 Experimental models

The relatively few experimental investigations on the aerodynamics of precipitation are mostly concerned with the terminal velocity of freely falling particles (see Section A.2), and the mechanics of blowing snow.

A useful technique for investigating blowing snow properties is to introduce simulated snow into a wind tunnel or water flume and observe the development of the particle patterns around scale models of buildings, fences, etc. A small number of special wind tunnels and water flumes has been built; most of these will be reviewed below.

The two main problems in performing experiments on blowing snow are: 1) satisfying the scaling criteria accurately, and 2) simulating the snow adequately. The complex nature of snow drifting phenomena make the determination of modelling criteria especially difficult. Conflicting requirements are encountered and it must be decided which may be neglected without serious loss of accuracy. It was not until about 1958 that a thorough study of the modelling problem of blowing snow was initiated at New York University. Scale factors were developed by dimensional analysis using the pi-theorem and by consideration of theoretical equations of motion for saltation (Refs. 44,61). In Ref. 46 scale factors are derived by using the equations of vertical transport and the threshold characteristics. A thorough study on the similarity criteria governing
the simulation of phenomena in snow deposition and snow transfer is given in
Ref. 33.

Choosing materials with which to simulate the blowing snow is a compli-
cated matter because many contradicting requirements are present and a compro-
mise must be made. An extensive search to find appropriate simulators for snow
in a wind tunnel (Refs. 61, A30, A31) involved testing various materials for
mean particle size, particle shape, density, terminal velocity, coefficient
of restitution, threshold velocity, ability to remain free flowing, small
variability in physical properties, etc. None of the low-density materials
tested (styrofoam, balsawood sawdust, mica, polystyrene, large cork particles,
etc) were considered to be suitable. Of the high-density materials tested
(alum, borax, table salt, mahogany, small cork particles, etc) only borax appeared
to more nearly approach the requirements for a modelled snow than any of the other
materials. A material used to simulate blowing snow in water flumes is fine
quartz sand (Refs. 33, A83).

In the open-return New York University wind tunnel, which has a test
section 3-1/2 ft. high by 7 ft. wide by 30 ft. long and a wind speed of 19
ft/sec, commercial borax of mean particle diameter 0.2 mm (model scale 1:10)
was used to simulate the blowing snow (Refs. 44, 61, A29, A30, A31). Before an
experiment was started the floor of the test section was covered with a layer of
simulated snow which extended about 13 ft. upstream of the modelled
objects, positioned near the centre of the test section. During a run the borax was
introduced into the airflow at the upstream end of the test section by means
of a hopper in the ceiling of the tunnel. Observation of the snow accumulation
patterns indicated that under suitable conditions a few hours test in a wind
tunnel may provide acceptable information that could not be acquired in less
than three to five years under natural field conditions.

Also at New York University a small wind tunnel (10 in. wide by
24 in. high by 8 ft. long) was employed to test collection efficiencies of snow
fences, using ground cork as a substitute for snow (Ref. A33).

A small open-circuit wind tunnel with a 30 cm x 30 cm x 170 cm test
section set in a cold room and using newly fallen snow carried in from the field,
was used to study the behaviour of real blowing snow particles (Ref. A67).

The closed-circuit wind tunnel described in Ref. A26 had a test
section of 2 ft. x 2 ft. x 10 ft. and a maximum wind velocity of 45 mph, and
was used to investigate the properties of various snow fence models at 1:24
linear scale. The materials that were used as a substitute for snow consisted
of flake mica and fine sawdust. The test results compared favourably with
those obtained in investigations with actual snow and fences.

As blowing snow and blowing sand have many properties in common, it
may be useful to mention an open-return wind tunnel constructed for investi-
gating blowing sand (Ref. A4). The test section had dimensions 1 ft. x 1 ft. x
30 ft. and was composed of 3 ft. long sections, jointed together and supported
at the joints by spring balances. By the change in the readings of these, the
rates of sand deposition and erosion, and therefore, by summation, the net flow
of sand past any section, could be measured at any place in the tunnel. The
sand used was screened to exclude all grains other than those between 0.3 and
0.18 mm in diameter.
In the Boundary Layer Wind Tunnel (8 ft. x 8 ft. x 80 ft.) at the University of Western Ontario a preliminary experimental study was performed in which small glass beads of mean diameter 72 μm were introduced into a turbulent boundary layer generated in the wind tunnel and their diffusion and dispersion analyzed (Ref. 5). This experimental method shows promise in replacing and/or complementing some full-scale experimentation.

Also at the University of Western Ontario a model study using a water flume and fine sand was performed to study the deposition of dry snow on roofs during particular snowstorms (Ref. 33). The water flume had inside dimensions 9-1/8 in. wide by 16-1/4 in. deep by 16 ft. long; the maximum flow velocity was about 1 ft/sec. Appropriate surface roughness was simulated with stones and crushed rock glued onto aluminum panels, placed along the flume bottom. The material used to simulate the snow was commercially available silica having a nominal particle diameter of 0.2 mm, and well rounded and similar to graupel particles (soft hail) in appearance. Although the results obtained with this particular sand-water model are not entirely representative of the full-scale process of snow load formation, the model was nevertheless useful to illustrate the interdependence of the various parameters influencing snow deposition on roofs. Model roof snow deposition obtained during relatively low wind speeds and lower but more probable snow fall rates, is generally considered to be representative of actual snow deposition.

Another water flume, employing sand and aluminum flakes to investigate blowing snow accumulation about model farm structures, is mentioned in Ref. A83. The use of drops of mercury to simulate rain in a water tunnel is proposed in Ref. 28.

Model experiments not directly related to terminal velocity or blowing snow have been performed at the Institute for Aerospace Studies: drops of liquid (milk and water) falling into a horizontal jet (Ref. 25), and waterdrops falling into an annular air-curtain enclosure or air dome (Refs. 24,37), both experiments with no side wind. The test results indicate the feasibility of protecting a portion of space from rainfall by means of air screens. The main scale factor derived for the air dome experiment has the form of a Froude number.

Other model experiments, performed in the UTIAS Subsonic Wind Tunnel, on the applicability of air screens as a means of protection, are discussed in Ref. A3. Upwardly blown plane air jets forming a screen were employed to protect an electrical power transmission station from wind-blown salt, emanating from an elevated source, using helium gas as a tracer to simulate salt spray contaminant. The investigation was not decisive but it indicated that reductions of the order of 70% in contamination can be obtained.

A discussion in Ref. 28, based on a study of the appropriate scale factors, indicates that it should be possible to predict rain impingement rates on buildings by suitable laboratory tests using either wind or water tunnels. Water tunnels would enable full-scale conditions to be more precisely matched, but they would be very inconvenient to use. Wind tunnels are more readily available and can adequately represent full-scale conditions. Water drops have the disadvantage that they can affect the wind tunnel structure, can be difficult to collect at point of impact, are somewhat large, and are difficult to generate at a precise size. Glass beads have the advantage of being readily available at known sizes, could be made to adhere to a model surface, and would not affect the tunnel structure.
A.2 Terminal velocity

A.2.1 General

An arbitrary particle of frontal area \( A_p \) moving with velocity \( V \) relative to a gaseous or liquid medium of density \( \rho \) is subjected to a drag force equal to \( C_D \rho V^2 A_p \). The particle drag coefficient \( C_D \) has experimentally been found to be a function of the particle shape, its orientation with respect to the direction of motion, and the Reynolds number \( Re = V l_p / \nu \), where \( l_p \) = characteristic particle length, and \( \nu \) = kinematic viscosity of fluid medium. The influence of acceleration on the drag coefficient (Refs. 30, A41) will not be considered because the following discussions are limited to steady motion. Numerous experiments have been performed on particles of a wide variety of shapes and materials to find their \( C_D = f (Re, \text{shape, orientation}) \) relationships.

The terminal velocity of a particle falling under the action of gravity in a fluid medium at rest (one-dimensional steady-state motion) is its constant velocity relative to the medium when its drag is balanced by its weight. As this Section A.2 will be restricted to heavy particles falling in air, i.e., the air density is much smaller than the particle density, the magnitude of the terminal velocity of an arbitrary particle then appears to be:

\[
V_t = \sqrt{\frac{2 I_p \rho_p g}{C_D A_p \rho}}
\]

where:

\( V_t \) = particle terminal velocity
\( I_p \) = particle volume
\( \rho_p \) = particle mass density
\( C_D \) = particle drag coefficient at velocity \( V_t \)
\( A_p \) = particle frontal area
\( g \) = gravitational acceleration
\( \rho \) = air mass density.

The main problems in calculating \( V_t \) are then to determine the particle size, shape, and orientation (and hence \( I_p, A_p, \) and \( l_p \)), and the drag coefficient. The following discussions are restricted to particles of interest to precipitation aerodynamics, i.e., solid particles, spherical and non-spherical (snow and hail), and liquid particles (waterdrops, rain), and will mainly concern single particles falling in unbounded fluid. Some information on the interaction of particles falling in groups will be included in Notes at the end of Sections A.2.2 and A.2.4.

A.2.2 Solid spherical particles

An understanding of the drag behaviour of solid spheres is basic to the study of precipitate particles, and therefore these will be discussed first.
The large number of investigations performed on solid smooth spheres of diameter \( d \) moving with velocity \( V \) in different fluids have shown that there exists a typical, rather complex relationship between the drag coefficient \( C_D \) and the Reynolds number \( \text{Re} = \frac{Vd}{\nu} \) see Table A.1, the first two columns. This function is also given in Fig. A.2 using linear coordinates; usually it is presented employing the more familiar log-log coordinates of Fig. A.2. See Refs. 39, A40, A51, A70, A71, A79.

Efforts to describe the whole curve of Fig. A.2 by one analytical function have not been very successful, although the function discussed in Ref. A2 is in remarkable agreement with experiment for Reynolds numbers up to about 5000. Various approximations of parts of the curve have been introduced (see for instance Refs. 18, A14, A34, A49, A71, A79). The approximate functions discussed in Ref. A58 agree within a few percent with numerical computations, using steady-state Navier-Stokes equations in the range \( 0.01 \leq \text{Re} \leq 400 \), presented in Ref. A52, A73. This numerical method appears to be able to predict theoretically accurate values of the drag on a sphere over a wide Reynolds number interval.

A useful and reasonably accurate division into three regions, covering the curve up to a Reynolds number of about \( 2 \times 10^5 \), is discussed in Refs. 39, A51, A70 (see Fig. A.2). These regions are the following:

**Region I:** covers the range \( \text{Re} \leq 0.3 \), where the inertia forces are negligibly small and only the viscous forces have to be taken into account. This region is often called Stokes' law, laminar, or streamline region. The function can be approximated very accurately by the straight-line relationship \( C_D = \frac{24}{\text{Re}} \). This was also discovered analytically by Stokes who found that in this region the drag \( C_D \frac{1}{2} \rho V^2 A_p = 3 \pi \mu V d_p \), i.e., the particle drag is a function of the first power of the particle velocity \( V \); see Refs. A14, A79.

**Region II:** covers the range \( 0.3 \leq \text{Re} \leq 1000 \), and is also called the intermediate or transition region; it partakes of both regions I and II. A reasonable approximation of this part of the curve appears to be the function \( C_D = 18.5/\text{Re}^{0.6} \).

**Region III:** covers the range \( 1000 \leq \text{Re} \leq 2 \times 10^5 \), where the viscous forces can be neglected; it is called Newton's law or turbulent region. The curve can here be approximated by the straight line \( C_D = 0.44 \), so that the drag equal to \( 0.11 \frac{1}{2} \rho V^2 d_p^2 \), i.e., a function of the second power of the particle velocity.

The terminal velocity of solid spheres can be written from Equation A.1:

$$ V_t = \sqrt{\frac{4 d_p^2 \rho_p g}{3 C_D \rho}} \quad (A.2) $$

Calculations of the terminal velocity can now be performed using either the three-region approximations discussed above, or the experimentally found \( C_D = f(\text{Re}) \) curve in Fig. A.2.

Using the approximations and Equation A.2 then gives:

In region I (\( \text{Re} \leq 0.3 \))

$$ V_t = \frac{d_p^2 \rho_p g}{18 \mu} \quad (A.3) $$
in region II \((0.3 \leq Re \leq 1000)\)
\[
V_t = 0.153 \frac{d}{\rho_p} \left( \frac{1.142 \mu 0.714 0.714}{0.286} \right) 
\]  \hspace{1cm} (A.4)

in region III \((1000 \leq Re \leq 2 \times 10^5)\)
\[
V_t = 1.74 \sqrt{\frac{d}{\rho_p} \frac{\rho_p}{\rho} g \mu 0.428} 
\]  \hspace{1cm} (A.5)

Calculating \(V_t\) by using the experimental \(C_D = f(Re)\) curve is rather more complicated but gives better accuracy (Refs. 39, A38, A58, A70). The use of a simple \(C_D\) vs. \(Re\) plot for prediction of either \(V_t\) or \(d_p\) involves trial and error, since both these terms are involved in both \(C_D\) and \(Re\). However, these trial and error procedures can be avoided by calculating first the terms \(C_D \cdot Re^2\) and \(C_D/Re\) because they do not include \(V_t\) or \(d_p\) respectively. Values of \(C_D \cdot Re^2\) and \(C_D/Re\) for spherical particles are given in the last two columns of Table A.1. Then, depending upon whether \(V_t\) or \(d_p\) is unknown, the value of \(C_D \cdot Re^2\) or \(C_D/Re\), respectively, can be calculated and the unknown obtained from the corresponding term calculated from \(Re = V_t d_p/\nu\) and Equation A.2:

\[
\frac{C_D}{Re} = \frac{\frac{1}{V_t} \cdot \frac{d_p}{\rho_p} \cdot \frac{1}{\nu}}{3 \rho_v} \left( \frac{d}{3} \right)^2 
\]  \hspace{1cm} (A.6)

Calculations for spheres of specific gravity 1, 2, and 3, referred to water at 4°C and falling in air at 70°F, have been performed (Refs. 39, A70), and the results are presented in Fig. A.3, together with the \(Re = \) constant lines.

**NOTE:**

When a number of particles are falling so close together that they influence each others flow field - i.e., each particle does not fall as it would in an infinite fluid - then the terminal velocity of the collection of particles can be different from that of a single particle falling in an infinite medium, the particle concentration and size being the main controlling parameters (Refs. 39, A14, A37, A39, A44, A46). Experiments with 850 \(\mu\)m glass spheres falling in the Stokes' law region indicate that at concentrations of from 0.1 to 3% by volume a considerable increase in terminal velocity can be observed (Ref. A46). Above 3% concentration the terminal velocity falls rapidly and at concentrations above 10% normal "hindered settling" is the dominant mechanism, characterized by a very much lower terminal velocity. Hence, for the 850 \(\mu\)m particles there apparently exists a striking difference between the behaviour of single particles and a collection of particles. It is therefore better in this case: not to ignore particle interaction at concentrations higher than about 0.05%. However, with decreasing particle size the change in terminal velocity becomes less pronounced. Experiments with 100 \(\mu\)m diameter glass spheres show no appreciable change in terminal velocity at concentrations up to about 1%, followed by a slight increase in the 1 to 2% range.
A.2.3 Solid non-spherical particles: snow and hail

Numerous analytical and experimental investigations have been performed to determine the drag of bodies of arbitrary shape (see for instance Refs. 39, 61, A37, A38, A40, A70). The drag properties of these particles are considerably more complicated than those of solid spheres, because of the influence of shape and orientation with respect to the direction of motion. (In the Stokes' law region a particle will generally retain its initial orientation during settling, whereas in the Newton's law region it will assume a position of maximum resistance).

This behaviour is of course most significant in the case of snow particles which exist in a wide variety of shapes and sizes (Refs. 33, A9, A17, A48, A58, A60). Analytical calculations of drag and terminal velocities of snow particles are therefore very rare, and most data have been obtained by means of full scale measurements using real snow (Refs. 33, 44, A15, A16, A17, A50, A58).

Experimental data on the terminal velocities of different kinds of snow crystals (Refs. 33, A58) are presented in Fig. A.4. The terminal velocities of plain dendritic, powder snow, and spatial dendritic crystals appear to be almost independent of their dimension, i.e., about 30, 50 and 57 cm/sec, respectively. Mean values of diameter, mass, and terminal velocity of the six crystal types are given in Table A.2.

Terminal velocities of snow flakes, i.e., aggregates of snow crystals (Ref. A58), are presented in Fig. A.5. The relation between terminal velocity and flake dimension appears to depend upon the shape of the flake and whether or not it is rimed. For a particular type of snow flake, however, there is little variation of $V_t$ with diameter, especially when the latter exceeds 2 cm. Experiments with models of snow crystals falling in various liquids are discussed in Refs. A43, A55.

Hailstones have a less complicated shape than snow crystals; they tend to spherical or elliptical with a more or less rough surface. Some experiments on real and model hailstones are presented in Refs. A25, A58.

A.2.4 Liquid particles: rain

A falling water drop is influenced by various physical factors, the most important of which are external aerodynamic pressure, surface tension, and internal hydrostatic pressure. As a result of the forces acting on the non-rigid drop its shape appears to be a function of the drop size, and it becomes distorted from the spherical for drops larger than a certain lower limit (Refs. A41, A49, A58, A59, A72, A74, A81, A84).

The existence of three drop-size regions can be distinguished, see Refs. A58, A72. (The equivalent drop diameter $d_e$ is the diameter of a sphere with a volume equal to that of the drop). These regions are:

\[
\begin{align*}
\text{no detectable deformation from spherical shape,} & \quad d_e \leq 280 \mu m \\
\text{slight deformation into oblate spheroid,} & \quad 280 \leq d_e \leq 1000 \mu m \\
\text{deformation is linearly related to drop size.} & \quad 1 \leq d_e \leq 9 \text{ mm}
\end{align*}
\]
Drops having a diameter larger than about 5 to 6 mm tend to be unstable and break up into a few large drops and a greater number of smaller ones (Refs. 31, A12, A14, A27, A42, A49, A58).

The behaviour of water drops appears to be influenced to some extent by air turbulence, so that laboratory and free-atmosphere measurements can give somewhat different results (Ref. A58). Data on the drag coefficient as a function of Reynolds number of water drops are given in Refs. A7, A41, A70.

Terminal velocities of water drops have been measured directly through experimentation or calculated from empirical drag data (Refs. A7, A17, A35, A49, A58). In Ref. A58 the results of Refs. A7 and A35 have been combined into a table giving the terminal velocities and Reynolds numbers of drops up to about 6 mm in diameter; these values are given in Table A.3, and the corresponding curve is drawn in Fig. A.6, together with the calculated results taken from Fig. A.3 on solid spheres of specific gravity one. The onset of drop deformation causes the curve to fall away from the sphere curve at $d_e \approx 280 \mu m$. The drop drag coefficient becomes appreciably larger than that of the corresponding rigid sphere and its terminal velocity becomes correspondingly lower.

Due to the complexities of the flows concerned it has not been possible to derive a simple formula for the terminal velocity of a drop of any size falling through air of any density, but some very complicated empirical equations are discussed in Ref. A58.

NOTE:

In Ref. A54 an experimental study is reported which gives some insight into possible interactions of drops in a rain shower. Single water drops of 2.9 mm diameter falling through a cloud of 5-10 $\mu m$ diameter droplets were observed to generate approximately cylindrical disturbances 5 to 10 drop diameters wide and 1340 drop diameters long, for average drop speeds of 619 cm/sec ($Re \sim 1360$), i.e., equivalent to 78% of their average terminal velocity of 794 cm/sec. It was concluded from these tests that in spite of the considerable extent of drop wakes, the fraction of air in rain occupied by wakes is rather small (4.5% for light showers with a precipitation rate 5 mm/h and consisting of 2.9 mm drops). Interactions between different drops must therefore be quite weak, particularly if the small velocity disturbances in the measured wake region are considered.
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<td>2.10</td>
</tr>
<tr>
<td>6</td>
<td>0.10</td>
<td>3.60</td>
<td>1.667</td>
</tr>
<tr>
<td>$1 \times 10^6$</td>
<td>0.13</td>
<td>$1.30 \times 10^{11}$</td>
<td>1.300</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>$1.80 \times 10^{12}$</td>
<td>$6.67 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

**TABLE A.1: Drag Coefficient and Related Functions for Spherical Particles**
<table>
<thead>
<tr>
<th>Shape</th>
<th>Diameter (mm)</th>
<th>Mass (mg)</th>
<th>Terminal Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needle</td>
<td>1.53</td>
<td>0.004</td>
<td>0.50</td>
</tr>
<tr>
<td>Plane Dendrite</td>
<td>3.26</td>
<td>0.043</td>
<td>0.31</td>
</tr>
<tr>
<td>Spatial Dendrite</td>
<td>4.15</td>
<td>0.146</td>
<td>0.57</td>
</tr>
<tr>
<td>Powder Snow</td>
<td>2.15</td>
<td>0.064</td>
<td>0.50</td>
</tr>
<tr>
<td>Rimed Crystals</td>
<td>2.45</td>
<td>0.176</td>
<td>1.0</td>
</tr>
<tr>
<td>Graupel</td>
<td>2.13</td>
<td>0.80</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**TABLE A.2:** Mean Values of Diameter, Mass, and Terminal Velocity of Snow Crystals

<table>
<thead>
<tr>
<th>Drop Diameter (mm)</th>
<th>Terminal Velocity (cm/sec)</th>
<th>Re</th>
<th>Drop Diameter (mm)</th>
<th>Terminal Velocity (cm/sec)</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.3</td>
<td></td>
<td>1.80</td>
<td>609</td>
<td>731</td>
</tr>
<tr>
<td>0.02</td>
<td>1.2</td>
<td>0.015</td>
<td>2.0</td>
<td>649</td>
<td>866</td>
</tr>
<tr>
<td>0.03</td>
<td>2.6</td>
<td></td>
<td>2.2</td>
<td>690</td>
<td>1013</td>
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<tr>
<td>0.04</td>
<td>4.7</td>
<td>0.12</td>
<td>2.4</td>
<td>727</td>
<td>1164</td>
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<tr>
<td>0.05</td>
<td>7.3</td>
<td>0.24</td>
<td>2.6</td>
<td>757</td>
<td>1313</td>
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<td>0.06</td>
<td>10.3</td>
<td>0.41</td>
<td>2.8</td>
<td>782</td>
<td>1461</td>
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<tr>
<td>0.08</td>
<td>17.5</td>
<td>0.93</td>
<td>3.0</td>
<td>806</td>
<td>1613</td>
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<td>1.69</td>
<td>3.2</td>
<td>826</td>
<td>1764</td>
</tr>
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<td>34.5</td>
<td>2.74</td>
<td>3.4</td>
<td>844</td>
<td>1915</td>
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<td>3.6</td>
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<td>3.8</td>
<td>872</td>
<td>2211</td>
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<tr>
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<td>115</td>
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<td>4.0</td>
<td>883</td>
<td>2357</td>
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<tr>
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<td>42.3</td>
<td>4.2</td>
<td>892</td>
<td>2500</td>
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<tr>
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<td>204</td>
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<td>4.4</td>
<td>898</td>
<td>2636</td>
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<tr>
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<td>246</td>
<td>97.5</td>
<td>4.6</td>
<td>903</td>
<td>2772</td>
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<tr>
<td>0.70</td>
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<td>132.</td>
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<td>907</td>
<td>2905</td>
</tr>
<tr>
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<td>325</td>
<td>172.</td>
<td>5.0</td>
<td>909</td>
<td>3033</td>
</tr>
<tr>
<td>0.90</td>
<td>366</td>
<td>218.</td>
<td>5.2</td>
<td>912</td>
<td>3164</td>
</tr>
<tr>
<td>1.00</td>
<td>403</td>
<td>267.</td>
<td>5.4</td>
<td>914</td>
<td>3293</td>
</tr>
<tr>
<td>1.20</td>
<td>464</td>
<td>372.</td>
<td>5.6</td>
<td>916</td>
<td>3423</td>
</tr>
<tr>
<td>1.40</td>
<td>517</td>
<td>483.</td>
<td>5.8</td>
<td>917</td>
<td>3549</td>
</tr>
</tbody>
</table>

**TABLE A.3:** Terminal Velocities of Water Drops in Air at 20°C and 1013 mb
Fig. 2  Aerodynamic Outline
Fig. 3  Back Panels with Hatches
Fig. 4 Fan RPM Control

Fig. 5 Electrical Wiring Diagram
Fig. 6  Screen Section with Side Panels removed

Fig. 7  Double Venturi Static - Pitot Tube Instrument
Fig. 8 Cross Section of Double Venturi Static - Pitot Tube Instrument

- Double Venturi
- Pitot Tube (mounted on other support rod)
- Spoilers

Scale: 0 to 4 inches
Fig. 9 Pressure Difference $\Delta p_{dv}$ of Double Venturi Static - Pitot Tube Instrument as a Function of Test Section Velocity Squared of UTIAS Subsonic Wind Tunnel.
Fig. 10  Mean Test Section Velocity $V_0$ as a Function of the Pressure Difference $\Delta p_{dv}$ indicated by the Betz Manometer

Temperature 77°F
Pressure 29.44 in. Hg
Fig. 11  Velocity Distributions in Central Cross Section of Test Section. (Values in ft/sec)
Fig. 12 Microphotographs (100X) of Glass Beads
Fig. 13  Calculated Terminal Velocities of Spherical Glass Beads of Specific Gravity 2.4 falling in Air at 70°F
Fig. 14  Bead Feed Box
Fig. A.1 Drag Coefficients for Spheres; Linear Coordinates
Fig. A.2 Drag Coefficients for Spheres; Log - Log Coordinates

- Inertial quantities negligible
- Laminar boundary layer develops
- Growth of eddies in wake
- Wake becomes fully turbulent
- Turbulent boundary layer forms

Region I
Region II
Region III

$C_D$ vs. $Re$
Fig. A. 3  Calculated Terminal Velocities of Spherical Particles falling in Air at 70°F
Fig. A.4  Terminal Velocities of Snow Crystals
Fig. A. 6  Terminal Velocities of Water Drops and Solid Spheres of Specific Gravity one
A description is given of the design, construction and calibration of a closed circuit wind tunnel, specially designed for studying the aerodynamic behaviour of precipitation (rain or snow) falling in a side wind blowing about buildings or other structures. The tunnel has a test section of 3-1/2 ft. by 3-1/2 ft. by 16 ft., and a maximum wind velocity of about 10 ft/sec. The particles selected to simulate rain and snow are spherical glass beads having diameters in the 20 to 150 μm range. In an Appendix a review is given of the current knowledge of the aerodynamics of precipitation.