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Polytechnic Institute of New York Environmental Wind Tunnel

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ABSTRACT

The design, construction, and calibration of the PINY Environmental Wind Tunnel is described, in addition to a discussion of the basic simulation requirements which led to the configuration and nominal test conditions.

The tunnel is an open circuit, closed test section facility with the capability of simulating the atmospheric mean wind profile and density distribution to an altitude of 2000 ft. It has a test section of 4 X 5 X 20 feet and a nominal velocity range between 0.25 and 35 fps. In the "clean" condition it can also be utilized for the more conventional testing of vehicle configurations.

Introduction

In the past few years interest has increased in the area of fluid dynamics of environmental problems; these relate directly to air pollution, design of industrial complexes, fire safety in high rise buildings, and both ground and air transportation systems, to mention a few. Therefore, a need for a wind tunnel capable of examining these problems by simulating the air flow patterns in the atmosphere has arisen.

Although there are currently several other similar facilities either in operation or in the design phase, the PINY Environmental Tunnel has certain combined features that make it unique in its test capability. For completeness, a brief summary of existing facilities is given here.

The Colorado State Meteorological Wind Tunnel [1] has a closed test section of dimensions 6 X 6 feet in cross-section and 88 feet in length which can be adjusted to establish negative, zero, and positive axial pressure gradients. It has a very low ambient level of turbulence equal to 0.1%, and can be used in either open or closed loop operation. Its ambient air temperature can be varied from

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32°F to 180°F at medium air speeds, and its humidity can be controlled. The velocity range is from 0 to 120 ft/sec. To obtain vertical temperature gradients, 40 feet of the test section floor can be heated or cooled to permit temperature differences between the plate and air. In Ref. 2, for example, a 2-foot thermal boundary layer was achieved with a 50°F temperature difference. Since this is created by natural convection, however, the thermal gradient cannot be altered significantly.

For studies in which thermal stratification is not necessary, but thick boundary layers are needed, Colorado State University has an open circuit wind tunnel with a 12 X 8 foot cross-section at the test section [3, 4]. The test section length is 52 feet and it has provisions for longitudinal pressure variations accomplished by means of an adjustable ceiling. This tunnel can produce a boundary layer of up to 2 feet thick at a velocity of 6 ft/sec.

Reference 5 describes a facility with a 6 X 9 foot test section. Although no heating or cooling capability exists for this facility, it can accurately simulate the atmospheric mean velocity distribution as well as the turbulence spectrum. This is accomplished by using spires with varying cross-sectional area in the vertical direction, which simultaneously alters the mean velocity distribution and the scale of turbulence in the tunnel.

The University of Western Ontario Wind Tunnel [6] has a test section of roughly 6 X 8 X 85 inches in length. Here, the boundary layer is achieved mainly by natural growth over the long section with some initial thickening created by rectangular blocks of random heights located at the test section entrance on the tunnel floor. Both the mean wind and the turbulence intensity are simulated quite well in this facility.

Airflow Developments Ltd. [7] manufactures a commercially available wind tunnel with an open test section. It has a velocity range of 5 to 15 ft/sec. The settling length is designed to minimize the boundary layer and to ensure a highly uniform flow into the observation chamber. This chamber is 7 feet high, 10 feet 6 inches wide and 7 feet 6 inches long. The working surface is 3 feet 6 inches wide which extends from the base of the air inlet to the rear wall exit. A 3 foot diameter turntable on the working surface is provided for model orientation and slots are provided to position horizontal slats in the intake side walls to allow modification of the vertical velocity profile.

Yamada and Meroney [8] describe a recently designed facility with a 2 X 2 foot test section which uses horizontal differentially spaced heating elements to provide the desired distribution of temperature. By varying the heater spacing the gradient in the test section can be altered significantly in contrast to the tunnels described above, where this is not possible. This particular design is similar to the PINY tunnel in which the thermal gradient is controlled by differential heating of fixed location heating elements. The maximum velocity capability of the Colorado State facility is a few feet per second.

Reference 9 describes the design of a channel with a 1 foot square test section, a uniform shear flow, and a mean velocity capability of approximately 40 ft/sec. In this facility the velocity distribution is achieved by having uniformly spaced channels in which screens of varying flow resistance are placed. In each channel the flow is almost fully developed at the exit and by proper design of the resistance screens, the linear velocity profile is obtained with nearly homogeneous turbulence. Here again, no effort was made to achieve a stratification of density since the main objective of this facility was to perform detailed studies of homogeneous turbulence.

The University of Manchester wind tunnel described in Ref. 10 was designed to provide linear distributions of both velocity and temperature in a test section of 20 X 20 feet. The heater section contains horizontal, nichrome bar heaters equally spaced and differentially heated by a power source connected by a network of control resistors to the heating elements. The velocity gradient is created by another grid, downstream of the first, designed to give a linear velocity profile. This tunnel is capable of a mean velocity of 6 ft/sec. with vertical temperature gradients of 5°F/ft.

The New York University wind tunnel described in Ref. 11 has a test section of 3.5 by 7 by 30 feet in length. It was designed and the construction initiated in 1948, although over the years many modifications have been made to improve its performance. The vertical temperature distribution in the test section is controlled by a heated grid spaced at 0.1 inch intervals. The surface boundary layer is produced by roughness elements on the floor of the tunnel and plates spanning the section, and the maximum velocity capability is 20 fps.

In examining the various requirements for simulation under different ambient conditions, and to obtain a facility with the maximum versatility of testing capability, the following features of the previously described tunnels were considered desirable:

1. large test section dimensions,
2. reasonably high velocity (~40 fps),
3. variable mean velocity gradient,
4. variable vertical density gradient, and
5. atmospheric turbulence simulation.

The practicality of obtaining any (or all) of these conditions is dictated by limitations on both space and funds. Within these constraints, however, the PINY wind tunnel facility was designed to incorporate the major items required to provide meaningful simulation.

It was determined, both on the basis of available space and on modeling criteria, that a wind tunnel with a cross-section of 4 feet high and 5 feet wide would be adequate. Therein, it is desired to simulate the atmospheric conditions of mean wind velocity, turbulence spectrum, and density up to roughly 2,000 feet above sea level. This is accomplished by nonuniform heating of the incoming air to a predetermined distribution of temperature to give the desired vertical density gradient, since the actual pressure variation with height in the atmosphere cannot be simulated in a small scale facility. The mean velocity profile is obtained by a nonuniform distribution of grid elements to create a velocity defect locally and thereby obtain a mean wind profile which duplicates the atmospheric boundary layer for various types of surface terrain. The turbulence is produced by distributed roughness and/or by the grids used to generate the mean velocity and the density profiles.

Following is a brief discussion of some factors which led to the above wind tunnel configuration, and the design criteria utilized to achieve the desired simulation capability. Also included are test calibration data for the tunnel in various modes of operation. These include the "clean" tunnel which would be used for aerodynamic tests of vehicle (both ground and air) configurations, the distribution of mean wind profiles corresponding to the atmospheric boundary layer without stratification, and both the temperature and velocity distributions resulting in the presence of the heating elements required for simulation of the atmospheric density stratification.

Wind Tunnel Design Criteria

The characteristics of the earth's surface boundary layer have been measured with respect to mean wind profile, turbulence spectrum, and density variation under a wide variety of conditions. Some of these results have been correlated and are summarized in Reference 12. These data were used to obtain the design test conditions for the PINY Environmental Tunnel.

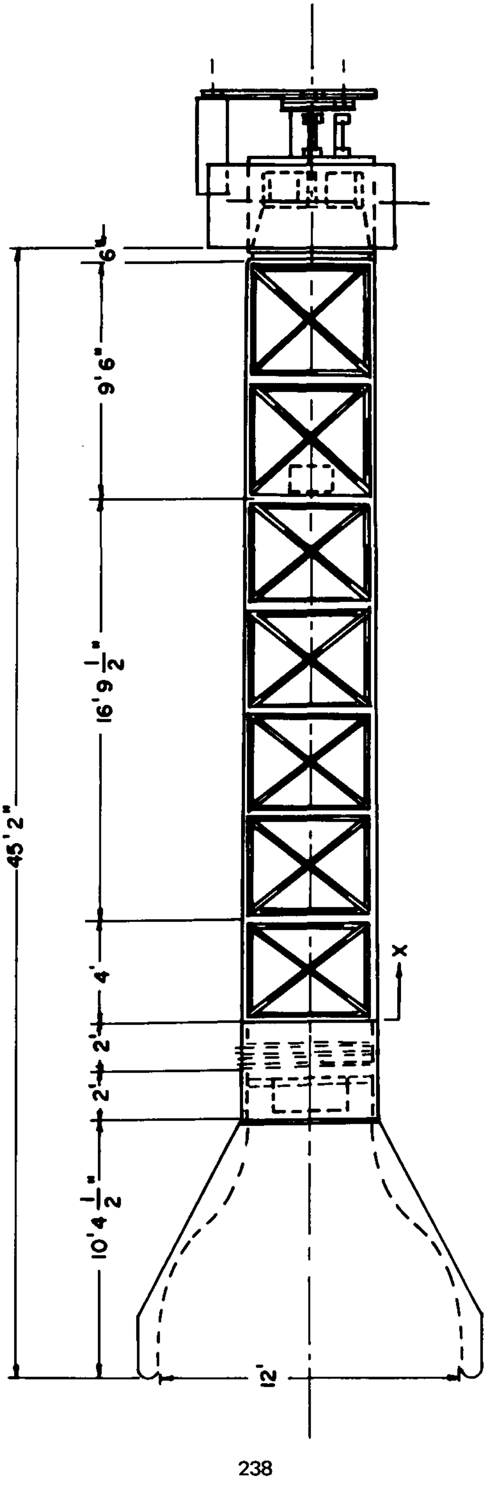
One of the main parameters affecting the mean wind distribution is the terrain over which the surface layer has traveled. This determines not only the thickness of the surface layer but also the power law variation with altitude. For example, over an open sea, the surface layer is a few hundred feet thick and the velocity varies with the 0.1 exponent of altitude. Over a heavily built urban area, at the other extreme, the layer is roughly 1,700 feet thick and the velocity varies with the 0.4 power of altitude. The design of the environmental tunnel, therefore, should include the capability of varying both the profile height and the power law exponent; this precludes the use of a naturally developed boundary layer.

Thermal stratification is another parameter with affects the stability of air masses, the mixing characteristics, and, for example, the coupling between external and internal flows in high rise buildings. This is also a significant effect in the creation of certain types of winds in mountainous regions, and in the atmospheric wave motion set up on the leeward sides of mountains. Problems peculiar to urban environments such as "heat islands" and thermal inversions are also directly related to the density distribution occurring under particular conditions. As a result, the simulation of this effect is quite important in a facility of the type described here, as well as the capability of varying the desired temperature gradient.

Turbulence structure [13] determines to a large extent the vertical mixing of air masses and the subsequent diffusion of both pollutants and natural particles. The formation of fog, for example, is directly dependent on the mechanism of turbulent exchange of heat and mass between the droplets and the vapor in the layer. No mechanism has been included in the present design for varying either the distribution or the scale length of the turbulence; however, this can be readily accomplished in a manner similar to that of Reference 5, if desired. Whether this can be done simultaneously with the simulation of mean wind profile and thermal stratification is questionable.

In an attempt to achieve complete simulation of the various atmospheric properties involved, a major limitation is on the maximum layer height under consideration. Since it is impossible in a stationary wind tunnel facility to simulate coriolis forces, the maximum vertical region that can be studied is on the order of 2,000 feet. Within this region, the mean velocity profiles, thermal stratification and turbulence structure can be reasonably well simulated, at least independently, depending on the maximum velocity desired, and the tunnel test section dimensions. It has been shown in Reference 13, for example, that various relationships exist between the tunnel height and the test section velocity if complete atmospheric simulation is to be achieved. This limitation generally specifies a minimum flow velocity for a particular tunnel height or, conversely, a minimum tunnel height for a given flow velocity. In addition, the simulation of thermal stratification in the atmosphere specifies a maximum flow velocity for a particular test flow height. As a result, the test envelope is bounded on both sides in terms of the test section height vs. velocity of the flow. Consideration of typical values of thermal stratification which exist in the atmosphere, as well as consideration of the surface roughness existing for various types of terrain (for example, a complex of buildings would have a significantly larger effective surface roughness than a field of grain or a forest) indicate that for test flow velocities up to 30 fps, a minimum flow height on the order of 3 feet is essential. Although the computational details of these considerations are not included here, these factors influenced the overall size of the facility. As shown in Figure 1, the test section of the PINY tunnel is closed and has interior dimensions of 4 feet in height, 5 feet in width, and 20 feet in length. This relatively short test section is made possible by the use of artificial boundary layer thickeners which will be described later in this paper.

The test section is constructed of plywood with steel reinforcing frames and has a number of thermopane windows to allow complete observation over the entire test section length. The basic design is an open circuit tunnel in which the air is drawn into a bell mouth contraction section from the surrounding atmosphere. This is followed by a section consisting of horizontal slats with a variable vertical displacement distribution to produce the mean boundary layer profile on the earth's surface. Following this is a section which contains horizontally oriented electrical resistance heaters which can be raised to a predetermined temperature from a control panel. The resulting vertical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9'6"
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45'2"
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2'
2'
10'4 1/2"
12'
X

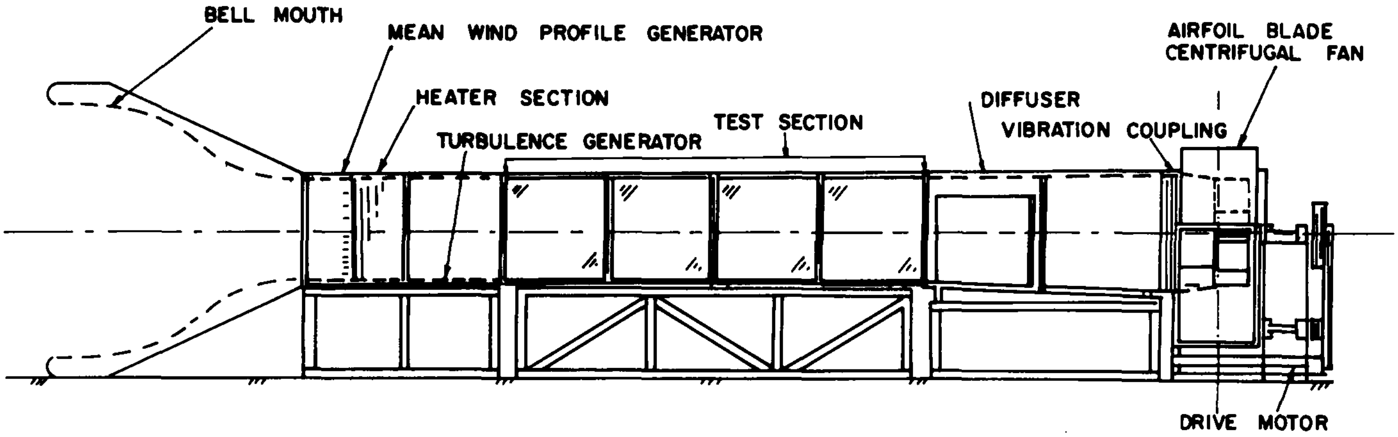


Figure 1. PINY environmental wind tunnel.

temperature distribution in the fluid downstream of this section will determine the vertical distribution of density, which allows simulation of thermal stratification in the atmosphere. Downstream of the heaters is a section with surface roughness elements distributed on the tunnel floor to generate the desired turbulence distribution in the immediate surface layer. These roughness elements have typically been constructed from pyramidal shapes or cubes, arranged in rows which are staggered in the streamwise direction. At this cross-section, which is the beginning of the test section, the vertical distribution of test fluid characteristics corresponds to the particular atmospheric layer to be studied.

Downstream of the test section is a diffuser which acts as a transition between the rectangular cross-section of the test section and the circular inlet of the blower system. The blower is an in-draft fan which discharges the test gas into the surrounding atmosphere. The open circuit configuration was chosen, rather than the closed return type, so that the air flow entering the test section be free of contaminants introduced by the model (smoke, water vapor, dust particles, etc.), and also to eliminate the necessity of recooling the test gas, which would otherwise be necessary.

Detailed design procedures for each of the tunnel components indicated in Figure 1 are described below.

BELL-MOUTH

The entrance bell-mouth, cf. Figure 2a, is required to provide a smooth transition from the stagnant, ambient atmosphere to the uniform flow in the test section. It is desirable in the design thereof to minimize the velocity overshoot that may occur locally if the fluid is accelerated too rapidly. To accomplish this, Reference 14 provides a technique based on the use of two cubic parabolas, matched at a predetermined location with the specification of continuous contour slope. As seen in the following section, from the tunnel calibration curves, this procedure worked quite well.

MEAN WIND DISTRIBUTION

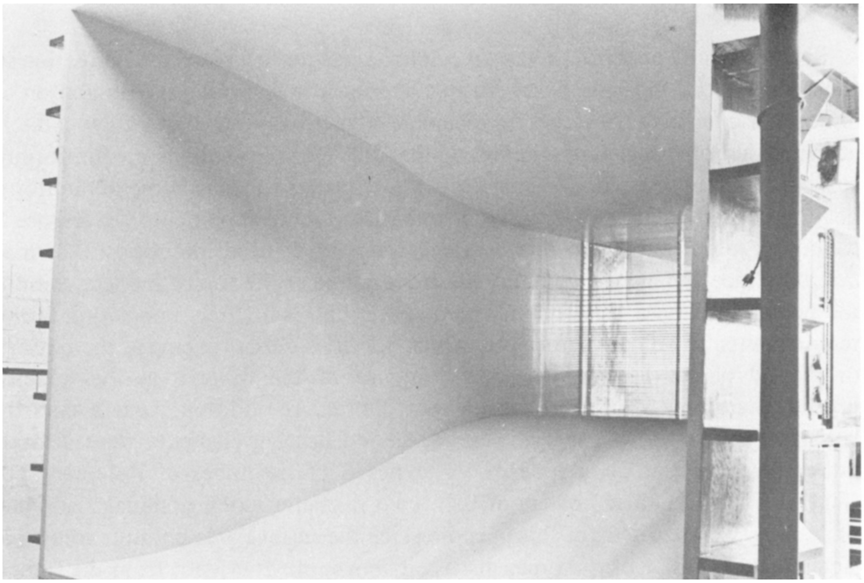
Considerable research has been performed with the aim of determining a technique of creating a shear flow with a given velocity distribution (in the present case, that required to simulate the earth's surface layer). Some of these have been described [1-11]. The approach taken here is to use slats with blunt edges and a fineness ratio of 0.10. These slats are positioned horizontally in the tunnel, downstream of the bell-mouth, with the capability of varying the spacing in the vertical direction; the design technique used to determine the spacing for any desired mean wind profile is presented in Reference 15. This variation of effective drag can produce a "boundary layer" profile across the entire four foot height of the tunnel. Photographs of these slats in position are shown in Figs. 2a and 2b.

HEATER SECTION

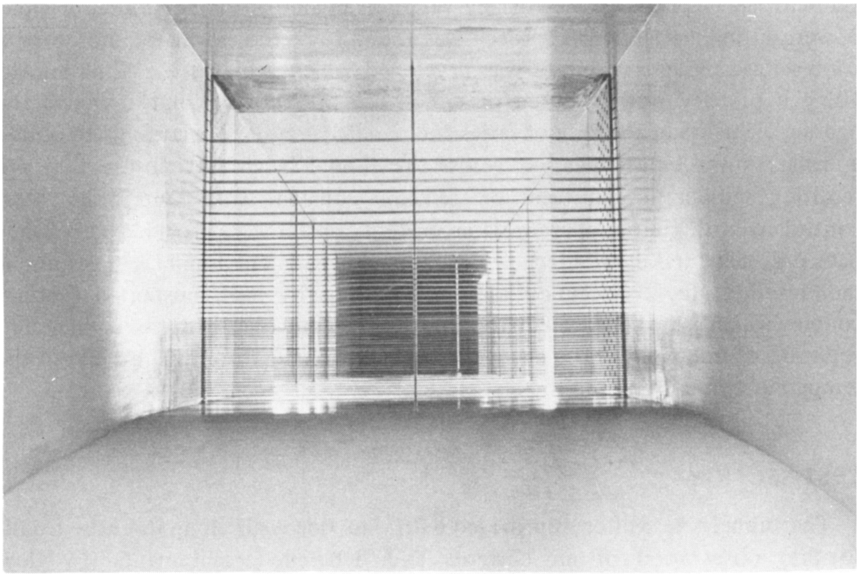
Since it is not possible to vary the static pressure in the vertical direction in the wind tunnel, the only other feasible approach to achieving the simulation of atmospheric density variation is to create a thermally stratified flow. This is accomplished by installing horizontal heating elements which are uniformly spaced, but supplied with varying amounts of power to provide the nonuniform heating desired, cf. Figure 2c. The differential spacing approach of Reference 8 cannot be used here since this creates a velocity distribution opposite to that desired. Since the higher temperatures are required at the top of the test section, the heater spacing in this region would be less; this is in direct opposition to the requirements on velocity, however, which specifies closer spacing at the bottom or ground plane. To minimize the influence of the heaters on the velocity profile, therefore, a uniform spacing was chosen. In addition, since a smooth, laminar type of flow was not desired, finned heating elements were utilized rather than the flat plate type of Reference 8 or the tubes of Reference 10. General Electric Calrod heaters of 0.26 inch diameter and a nominal resistance of 5 ohms were chosen for this purpose since the surface area per unit volume is larger than in either of the types discussed above; this is evident from the finned configuration as seen in Figure 2c. Ideally, it would be desirable to have an automatic controller on each heating element (or on each group of 2 or 3 elements) to provide complete versatility with respect to the desired thermal gradient, and to compensate for any variation in ambient temperature, or input power, during a test. This approach was found to be too expensive; moreover, a compromise design procedure was developed which achieves the same results. Using a primary power source of either 120 or 208 volts and arranging the heating elements in a variety of series and parallel circuits, it is possible to obtain a linear power input variation across the tunnel height. To insure that the resulting temperature distribution remains constant with time, four West controllers with continuously variable current control were provided across four banks of elements, distributed over the tunnel height. The tunnel temperature is monitored in the test section at four locations by iron/constantan thermocouples which provide the feedback input to the controllers. In this manner, any variation of input power, or change in ambient temperature, will not affect the temperature distribution in the test section.

TEST SECTION

The tunnel test section is provided with glass side walls along its entire length so that observation of air currents and detailed measurements (by flow visualization techniques) can be readily obtained. The side walls are constructed using four panels of Pittsburgh Plate Glass thermopane, as seen in Figure 2d. This also acts as a thermal insulation barrier and helps maintain the stratification produced by the heating elements.

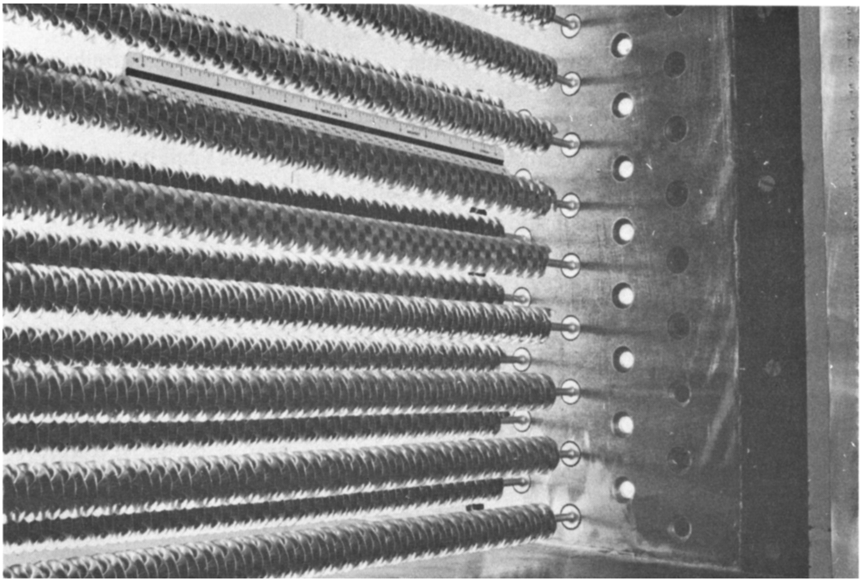


(a) Belmouth.

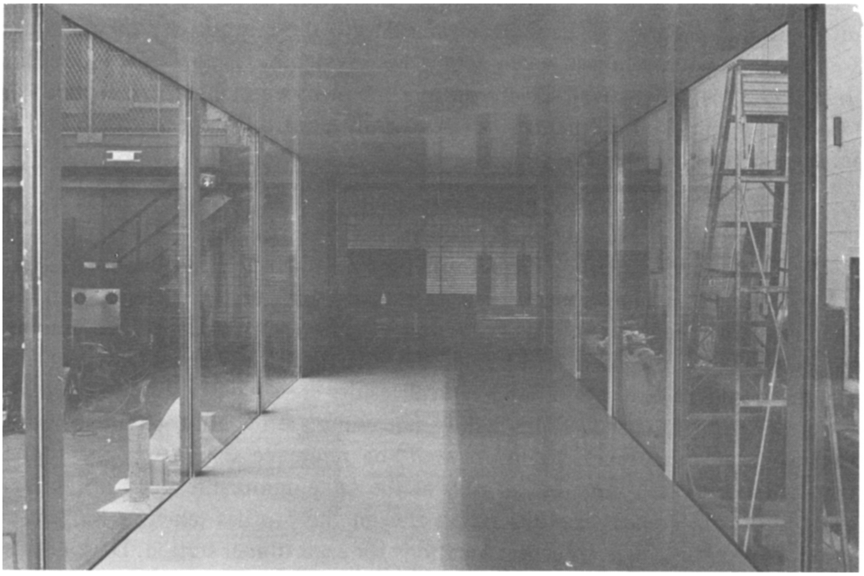


(b) Mean wind generator.

Figure 2. Environmental wind tunnel photographs.



(c) Heater section with elements installed.



(d) Test section.

DIFFUSER

Since the entrance to the fan is circular, a transition duct is required to join the test section (4 X 5 feet) to the fan (50-foot diameter). This is constructed of plywood and contains an access door and an instrumentation flange where test models may be inserted, and instrumentation tubes and wires can be led into the tunnel. Following the diffuser is a short rubber duct which acts as a vibration isolation attachment between the tunnel and the fan and drive mechanism.

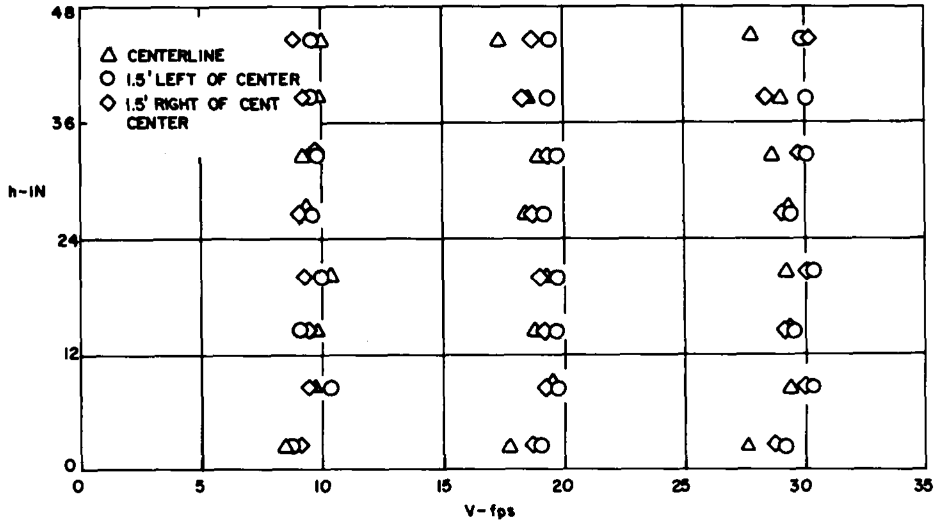
FAN AND MOTOR DRIVE SYSTEM

Since a nominal maximum velocity of 35 fps was desired, a fan with a volumetric capacity of roughly 40,000 CFM was required. Examination of various fan characteristics including such factors as noise level, variable speed operation, and low speed performance, dictated the selection of an airfoil bladed centrifugal fan. The American Standard model 490 was chosen for this purpose since the available flow rates were in the required range. Computation of the total static pressure drop through the tunnel including the bell-mouth, mean velocity grid, heater elements, and test section resulted in the requirement of a 20 h.p. motor to achieve the maximum velocity. Since variable speed is an essential feature of the tunnel, a General Electric SCR Varidrive system was also installed. This provides a continuous variation of fan speed from a dead stop to maximum rpm. At the low speed end of the variation, however, both control and constant speed are difficult to obtain due to the insensitivity of the motor drive unit. As a result, a two speed pulley drive system was added; the high speed arrangement providing a direct drive while the low speed range corresponds to a 10:1 reduction. In this manner, an accurately controlled speed capability of between 0.25 and 35 fps can be achieved.

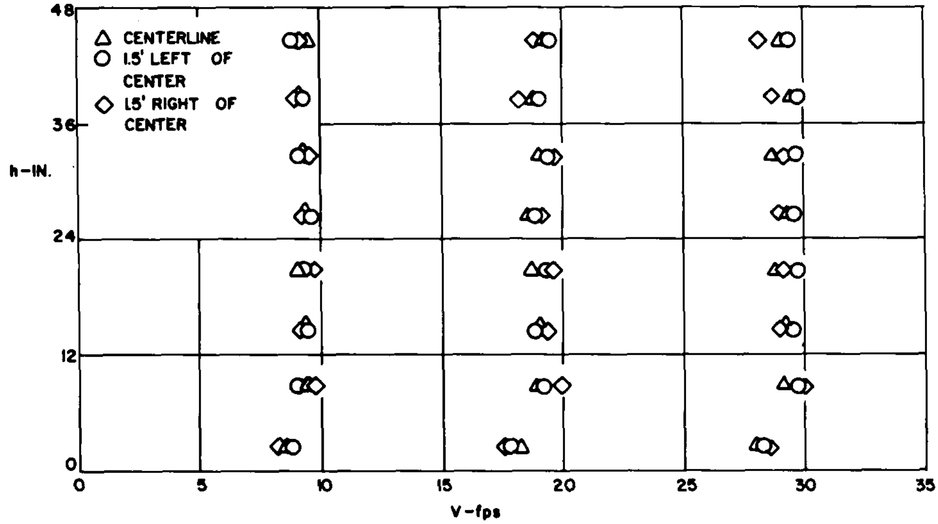
Calibration Results

The PINY Environmental Tunnel was first run in the "clean" configuration, i.e., without the heating elements, mean velocity grid, or turbulence generators installed. The speed control was varied to give calibration data for three nominal test section velocities of 10, 20 and 30 ft/sec. Profiles were obtained at five stations along the test section and typical results are shown in Figs. 3a and 3b. Since the major function of the facility is to simulate the atmospheric layer, no particular care was taken to insure that the reference velocity in the tunnel remained exactly the same for all runs at the same nominal test condition. As a result, some differences are observed between the profiles taken at the left of center, center, and right of center locations for each tunnel station. Despite this, the flow is seen to be quite uniform both across the tunnel and with respect to axial location, with some improvement in flow uniformity as one progresses downstream.

Since the first research project to be tested in this facility corresponds to an



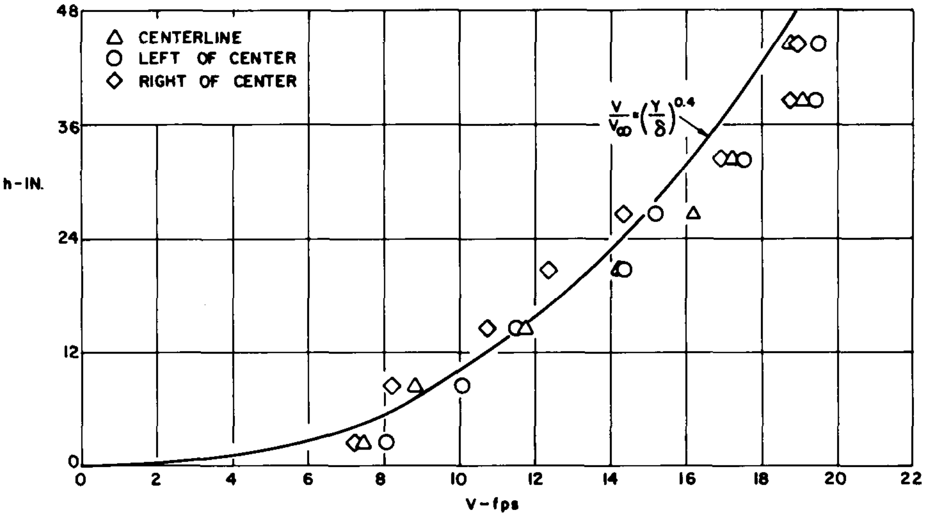
(a) X = 89.125



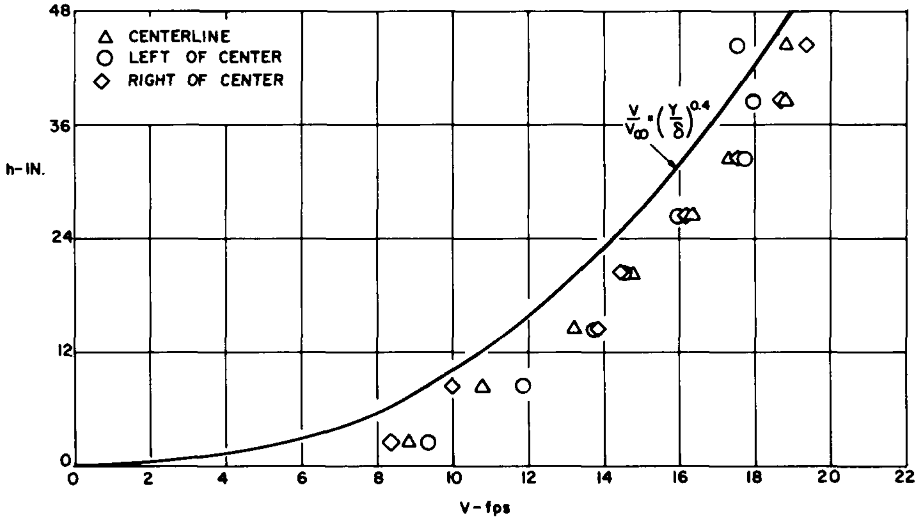
(b) X = 239.625

Figure 3. Velocity profiles—clean tunnel.

urban environment, the mean wind profile corresponding to the velocity varying with the 0.4 exponent of altitude was chosen. The horizontal slats were adjusted to produce the mean velocity profiles shown in Figure 4. Here the nominal wind



(a) X = 89.125



(b) X = 139.125

Figure 4. Velocity profiles—mean wind profile over urban area.

velocity (at altitudes over 1,700 feet) was 20 ft/sec. It is seen that relatively good agreement is obtained with the desired distribution except for a region close to ground level. This was anticipated since the ground roughness elements were not in place during these tests. Again some difference in magnitude between various lateral and longitudinal velocity profiles is observed although the general distribution is reasonably well-behaved. It may be noted that the boundary layer along the upper tunnel surface grows in the downstream direction, thus causing decreasing agreement with the analytical curve along the tunnel ceiling. Inclusion of the surface roughness elements and further modification of the slat locations, however, should improve this distribution.

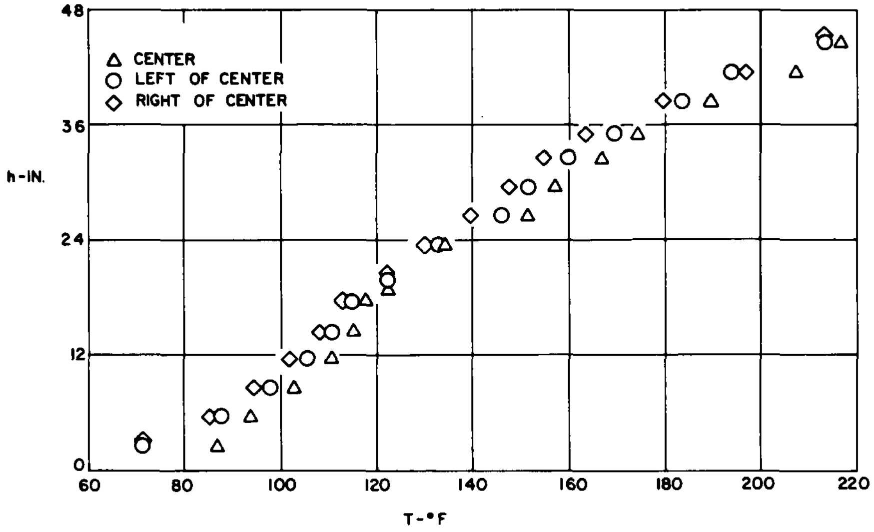
Each individual research program conducted in this tunnel will, in all probability, require a different mean velocity profile due to the type of terrain, model scale, and atmospheric layer height of interest. Therefore, the detailed placement of slats for any desired mean wind distribution will be performed under each project; for present rough calibration purposes, it was deemed sufficient to obtain one typical profile to indicate that such a mean wind distribution can indeed be obtained from the current facility. It may also be noted that the "urban" profile is the more difficult to obtain since it corresponds to a significant velocity gradient over the entire altitude range; the other typical profiles are much more uniform except in the vicinity of the ground plane since they correspond to lower values of the exponent in the formula for the velocity distribution with altitude.

Figure 5 presents the temperature distribution at two typical locations in the tunnel at the maximum heater settings. In terms of the vertical density distribution, this simulates altitudes up to 8,000 feet, which is considerably higher than the desired simulation range. In terms of the Richardson number (where $Ri = (gL^2/u^2)\ d \ln \rho/dy$) this distribution corresponds to a value of 3.5 based on tunnel height. If the model length is used in the definition, a Richardson number of unity can be achieved with a model length of 2 feet. This result indicates, therefore, that practical problems of interest can be realistically simulated in this facility.

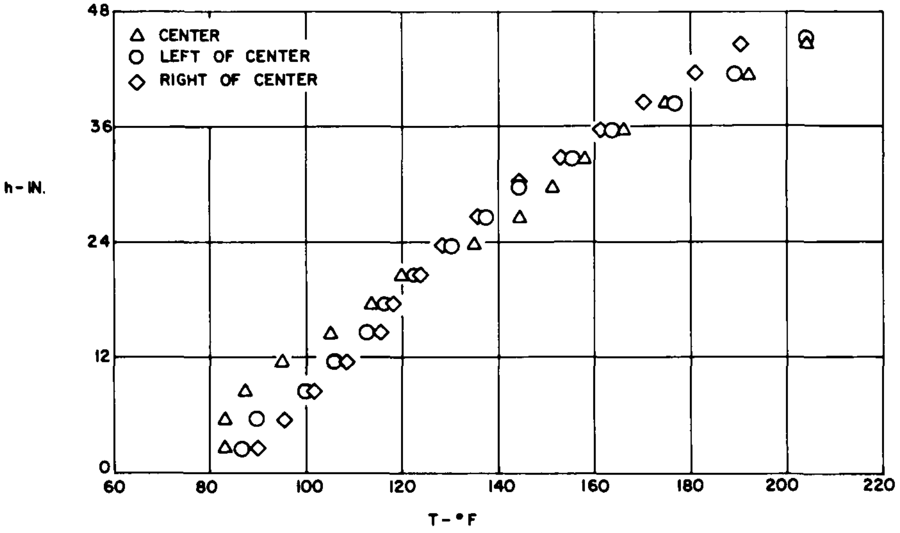
Research Studies

The first project to be studied in the PINY Environmental Wind Tunnel is the measurement of external wind loads on a building in the vicinity of the Twin Towers in lower Manhattan. The building was the site of full scale fire safety tests which are fully described in Reference 16. It was 22 stories in height and had an "H" shaped planform which was typical of many high-rise buildings designed in the early 1900's. Due to this configuration, as well as the complex structures in the surrounding area (the location borders on the Wall Street area), some strange flow patterns were observed in the interior of the building under certain external wind conditions. To help explain these anomalies, a scale model was built of lower Manhattan covering an area of one-half a square mile. Photographs of this model installed in the tunnel are shown in Figure 6.

The model can be rotated to simulate various wind directions and is instrumented to obtain surface pressure distributions over the entire model.



(a) X = 42.75



(b) X = 239.625

Figure 5. Temperature profiles at velocity of 3fps.

Flow visualization equipment is also available to evaluate the external flow patterns in the vicinity of the test building.

During the full-scale tests, some external pressures were measured on the

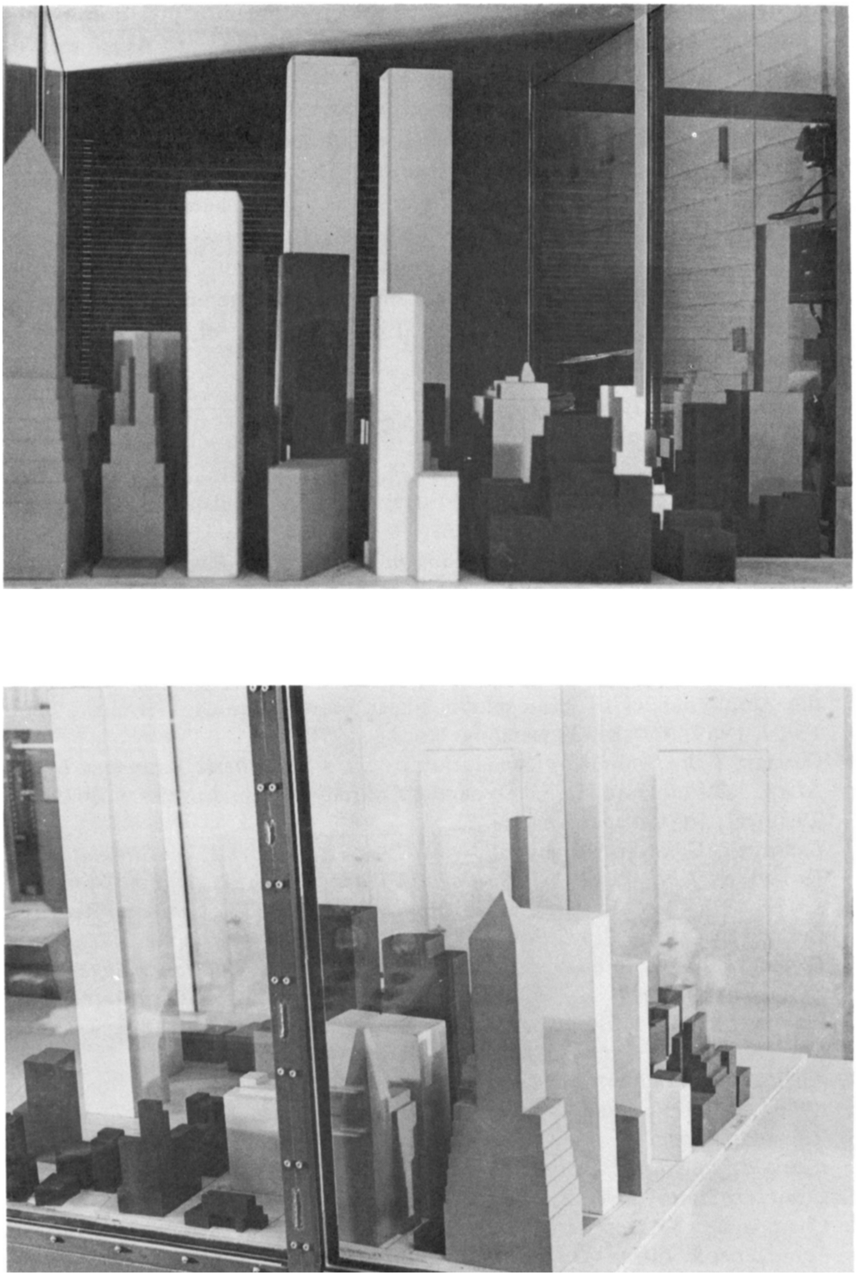


Figure 6. Photographs of test model.

actual building. Unfortunately, the wind velocity and direction during these measurements was not the same as occurred during the fire tests. As a result, the wind tunnel scale model tests will serve a twofold purpose. First, the accuracy with which the full-scale data can be predicted in a wind tunnel test will be evaluated by comparison of the data obtained on the actual building and in the tunnel. This will ascertain the importance of total simulation of density, mean wind velocity distribution, turbulence, etc. Once this has been determined, the model can then be oriented to produce the atmospheric wind conditions existing during the full-scale fire tests. The analysis of the measured external pressure distribution on the building model can then be used to attempt to explain some of the observations. This study is typical of the variety of tests that can be performed in such a facility.

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