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OF WIND FLOW AROUND BUILDINGS AND WITHIN
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AN ASSESSMENT OF THERMAL COMFORT AND POLLUTION DISPERSION POTENTIALS REVEALED BY PHYSICAL MODELING IN A WIND TUNNEL FACILITY OF WIND FLOW AROUND BUILDINGS AND WITHIN URBAN AREAS

by

Marcio Villas Boas

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF ARCHITECTURE

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HOUSTON, TEXAS

May, 1979
ABSTRACT

AN ASSESSMENT OF THERMAL COMFORT AND POLLUTION DISPERSION POTENTIALS REVEALED BY PHYSICAL MODELING IN A WIND TUNNEL FACILITY OF WIND FLOW AROUND BUILDINGS AND WITHIN URBAN AREAS

by

Marcio Villas Boas

A physical modelling experiment was conducted in an environmental wind tunnel facility to assess the air flow characteristics in and around structures and within spaces formed by two or more structures. The study sought to extend the current knowledge about air movement in urban areas by addressing the joint problem of achieving favorable thermal comfort and ambient air quality conditions in outdoor spaces.

The influence of wind speed and direction on the pollutant concentration distribution on the lee-side region of isolated porous and nonporous structures, and in the area bounded by two or more structures was studied. The potential for through-ventilation of downstream structures as a function of the distance and porosity of upstream structures was also evaluated. In this investigation, thermal comfort for warm and humid regions and ambient air quality served as criteria for assessing the performance of the outdoor spaces.

It was found that the use of pilotis or arrangements of structures that permitted penetration of horizontal wind into their lee-side region of frequent intervals allowed reduction of the distance between upstream and downstream structures while maintaining the potential for
through-ventilation in downstream structures. Measurement of outflow air velocity immediately adjacent to the lee-side window openings of structures indicated identical values for different elevations. This resulted from equal pressure differentials at each elevation.

The use of porous structures in urban areas was found to be an important element for enhancing both thermal comfort and air quality conditions, regardless of wind direction, when the source of pollution is at grand levei. It was also observed that similar conditions resulted when low-rise and high-rise structures are combined in an urban pattern. However, for a pollutant source elevated above ground level it was found that the presence of porous or nonporous high-rise structures downstream from low-rise structures created unfavorable air quality conditions in the space on the windward side of the high-rise structures.

Adherence to the following general principles related to air movement was concluded as enhancing thermal comfort and ambient air quality in urban areas situated in warm regions: 1) building and urban furniture patterns within settlements must permit the wind to enter the living spaces; 2) activities that produce larger amounts of contaminants must be located in such a way that pollution plume dispersion does not penetrate and accumulate within living precincts; 3) building and urban furniture in urban areas must have some degree of porosity near street environs where motor vehicles and pedestrians coexist; 4) shelter must be located between roads carrying heavy traffic and sites for long-term outdoor activities.
Dedication

This is dedicated to three very special girls of my life: my wife Benigna and my daughters Marcia and Isabela, and to two men who would be very proud of this accomplishment: my late father-in-law Francisco and my late father Waldemar.
Acknowledgements

I would like to express my thanks to all those who helped me in this investigation. In particular I would like to acknowledge the members of my dissertation committee, Mr. Peter Rowe, Dr. Nat Krahl, Dr. Frank Worley, Jr., and Mr. Antonio de Sousa Santos, whose experience influenced my work significantly. To Mr. Rowe, the Chairman of my committee and my advisor during my course-work, special thanks are due for his readiness to discuss and comment on my work, and for his continued encouragement in pursuing this research. To Dr. Worley for giving me access not only to the wind tunnel facility but also for introducing me to the interesting field of physical modeling, I owe a lasting debt of gratitude. I would like to express my appreciation for the support of Dr. Clelia Capanema, Dr. Jose Galbinski, Mr. Muhdi Koosah and my wife Benigna Villas Boas who reviewed many parts of my dissertation. Thanks are also due to my daughter Marcia for her patient help in correcting my "miswritings" and misspellings and for typing my preliminary drafts into a sound paper. Thanks to my Mexican friend, Mr. Arturo Gallegos, who helped me in setting the wind tunnel instruments and constantly provided sound suggestions during the research. Finally, I would like to express my appreciation to Mr. Hubert Alton Wood, Jr. "Chipwood", who prepared the film used in the concentration visualization, and to the Rice Center for Community Design for financing part of my investigation.
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CHAPTER I

INTRODUCTION TO THE PROBLEM

Man has obtained many benefits from the industrial and technological revolution that are reflected in increased standards of living. A considerable number of socio-economic advantages have resulted from concentration of economic activities within cities and urban regions. However, this concentration has also resulted in social costs that have reduced the quality of urban life. Among these costs are the direct contribution made to air pollution and to increased thermal stress. Recalling a definition of efficiency wherein society's benefits are maximized as resources are allocated efficiently, Schreiber, Gatos and Clemmer (1976) observed that pollution represents a case where benefits are not maximized. Correcting for this inefficiency cannot help but increase benefits to society and improve the standards of living for many people. The same observation can be made about increased thermal stress.

Complete elimination of air pollutants is not economically feasible nor socially desirable, so that some contaminants will always be released into the environment. However, it is in society's interest that the amount does not allow concentrations to exceed limits beyond which damage to man and nature may occur.

Air pollution and thermal comfort in cities can be controlled to a certain extent through urban and building design (A Guide for Reducing Air Pollution through Urban Planning, 1971; Bach, 1972; McHarg, 1969; Peterson, 1971). Improved environmental quality can be achieved with changes in the spatial organization of urban areas and with changes in
building patterns. Alternative transportation systems and settlement patterns can reduce energy consumption and the release of contaminants within the environment.

The control of all environmental factors affecting the quality of urban life has become technically more feasible and socially more desirable than ever before. However, most contemporary building and urban designers have failed to realize the potentialities of a healthy urban life (Fitch, 1976). Modern man has been living in opposition to nature, and cities have become distortions of the natural laws of energy conservation (Knowles, 1974). The meaning of an integral architecture that "would endeavor to secure through site planning and site development, through orientation to sunlight and wind, a result that can otherwise be obtained through an expensive mechanical contrivance" has been forgotten (Mumford, 1975).

Cheap energy and mass production have made it possible to erect buildings without climatic responsiveness, which look more or less the same throughout the world (Ryd, 1972), in spite of the great range of human needs and energy conditions. Curtain-wall buildings have been built in Stockholm (60° North), Houston (30° North), Brasilia (16° South), and elsewhere.

In spite of a continuing high demand for comfort, the energy crisis and renewed environmental consciousness suggest a more rational use of natural resources and a greater reliance on the natural control of atmospheric variables through building and urban design. It seems reasonable to expect that a more appropriate balance between man and his natural environment can be struck that will in turn enhance the general quality of life.
Problem Situation

Ventilation is the most important controllable atmospheric element in building and urban design for achieving environmental quality. It is the key component in the dispersion and dilution of pollution generated by man's activities and in the achievement of thermal comfort within and around buildings.

Many models have been reported which describe how the ambient atmospheric environment acts on man (Bassiakos, 1968; Givoni, 1969; Kamon, 1975; Koenigsberger et al., 1974; Olgay, 1953 and 1963; Sargent and Tromp, 1964). Each of these models combines two or more variables of ambient air temperature, humidity, radiation, and air motion in a single comfort index. They show that at higher temperatures combined with higher humidities, ventilation is critical for achieving thermal comfort. At low humidities ventilation is shown to be of little help, and, at low temperatures, inappropriate. In the latter case, the chilling effect of wind tends to accentuate the feeling of discomfort.

In contemporary architecture, the design for natural ventilation has not been as well considered as one might expect in many of the warm, humid regions of most so-called "developed" and "developing" countries. An overall "fitness" of building and urban design form to other variables of the atmospheric environment is also lacking in these regions. This is especially true for dense urban areas. In more economically advanced countries there has been a strong tendency to control conditions in the enclosed spaces by mechanical means to the level desired. This practice is, of course, highly energy-consuming. In those regions where only a few people can afford mechanical control, the lack of "fitness"
of structures to climate has resulted in unnecessary overheating of spaces and a consequent imposition of additional thermal stress on individuals.

With only a limited knowledge of air flow patterns in urban areas, it has been very difficult to explicitly devise control measures. This lack of knowledge has also meant that very little consideration has been given by designers to localized air pollution (A Guide for Reducing Air Pollution through Urban Planning, 1971). Besides an apparent lack of established procedures and effective legal tools to deal with the problem, it has been suggested that there is a lack of any precise knowledge of the effect that the arrangement, design, and operation of building elements have upon air pollution within a urban environment.

At present, most of the available information concerning air flow patterns inside and around buildings is derived from simulation of natural air flow characteristics in wind tunnel facilities (Reed, 1953; Caudill, Crites, and Smith, 1951; Caudill and Reed, 1952; White, n.d.; Wise, Sexton, and Lillywhite, 1965; Givoni, 1968; Givoni and Paciuk, 1972; Evans, 1972). Except for Givoni (1968) and Givoni et al. (1972), whose studies were concerned with particular building arrangements in urban area, the others studied air flow inside buildings or in the vicinity of a very small number of structures. Apart from general conclusions about appropriate building arrangements, forms, and special features, previous research generally lacks information on the potential for natural ventilation in buildings, particularly those situated downstream of other buildings, as well as on the overall effect of a built-up area (i.e., a larger group of structures) on downstream flow patterns.
Most of the information relating pollution emissions to ambient pollutant levels has been provided by mathematical models (Busse and Zimmerman, 1973; Christiansen and Porter, 1976; Christiansen, 1976; Lamb, 1971; Miller and Holworth, 1967; Pasquil, 1974; Seinfeld, 1970; Turner, 1970). These models, however, are not capable of predicting pollutant levels near obstructions created by buildings and/or urban furniture or of predicting levels in the vicinities of highly irregular topography encountered in built-up areas of cities. These omissions from the models are largely due to difficulties in describing air flow characteristics within such obstructed or irregular areas.

Wind tunnel (physical) modeling has been used in order to assess the effect of flow patterns on diffusion of contaminants (Cermak, 1977; Hoydysh, Griffiths, and Ogawa, 1974; Munn, 1967; Robins and Castro, 1977 and 1977). However, so far, the sparse results do not permit the establishment of sound guidelines that can be used by urban designers, to improve ambient air quality conditions in the vicinity of buildings.

The present study was directed towards obtaining information that is lacking in prior research on air flow and contaminant dispersion in urban areas. It is hoped that the experimental results presented here will yield useful design-related information about the use of cross-ventilation for the purpose of realizing thermal comfort and pollution dispersion.

**Purpose of the Study**

The present study was designed to provide building and urban designers with a basis for determining whether efficient ventilation in buildings and significant dissipation and dilution of pollutants can
occur for selected urban patterns and building groupings. Specifically, the data collected yield information on wind speed and direction and concentration of pollutants in the vicinity of isolated buildings or groups of buildings.

Design for natural ventilation to achieve thermal comfort is one of the major requirements for settlements in the world's tropical and subtropical regions. It is within these regions that a large proportion of the world's population lives. A large percentage of this population is of a very low income and unable to afford any mechanical means of environmental control. In more affluent areas of these regions (such as in the United States), design for natural control has been proposed to offset the increasing costs (and shortage) of energy-producing natural resources. Concern for environmental quality has been raised throughout the world, so the evaluation of the effects of urban structures on aid quality will have widespread application.

**Conceptual Assumptions and Theoretical Framework**

It was assumed in the present research that wind tunnel modeling is a reliable technique that closely simulates air flow characteristics around an isolated building and within groups of buildings in a urban area. Model tests in wind tunnels have been successfully carried out to simulate building responses to natural wind conditions at sites where resources were not available to allow extensive field investigations (Robertson and Chen, 1967). Reasonable agreement between full-scale wind pressure measurements and flow pattern simulation in a boundary layer wind tunnel has been found by Dalghesh, Wright, and Schrieger (1967), for the case of wind load. Huitron (1977) has extensively
revised the literature on wind tunnel studies and has described a series
of experiments where results from wind tunnel modeling were found to be
in close agreement with field data describing mean velocity and turbu-
lencc intensities in the longitudinal and vertical directions. Wise,
Sexton, and Lillywhite (1965) have studied air flow through urban areas,
in a short wind tunnel, and found that full-scale observations of air
speeds in buildings coincided with results obtained from similar arrange-
ments tested in wind tunnels. Koenigsberger et al. (1974) have reported
a series of studies in Australia, where results similar to Wise et al.
(1965) were found from wind tunnel modeling of various building group-
ings. Robins et al. (1977 and 1977), have investigated the plume dis-
perssion in the vicinity of a surface mounted cube with the use of a wind
tunnel facility and have found that both the field and the concentration
field examining by the experiment agreed well with other onsite experi-
mental investigation in the vicinity of buildings.

Many research workers have described facilities and techniques
required to obtain a good similarity between natural and simulated flow
characteristics. Thick turbulent boundary layers with large turbulence
intensities are required for simulating flows in a wind tunnel to obtain
a close similarity with atmospheric shear flows. Cermak et al. (1970)
have described techniques to develop such flows in both larger and
smaller tunnels and have suggested that large tunnels with a test sec-
tion 20–30 m in length demonstrate higher similarities with experimental
studies than results obtained from smaller tunnels. Huitron (1977) has
reported the simulation of stability from neutral to moderately stable
air with the use of a "Meteorological Wind Tunnel" (Colorado State
University). These results were obtained by heating and cooling both the floor and the ambient air. He has also simulated different stabil-
ities in an "Environmental Wind Tunnel" (University of Houston) by plac-
ing appropriate devices upstream of the model. Hoydish et al. (1974) have investigated the requirements for modeling an urban region in order to develop a picture of the overall flow patterns and have described the characteristics of the model to allow the velocity, turbulent intensity, and stress profile to adjust from small to large roughness values that are encountered in urban areas. Their research describes procedures that can be used so as to allow the region studied to be outside the transition zone.

From the foregoing one can conclude that there is a significant number of experiments which suggest that wind modeling provides a close similarity to natural conditions with respect to air flow characteris-
tics.

The facility used in this research is a large wind tunnel (En-
vironmental Wind Tunnel), described by Huitron (1977), having the capa-
bility of generating the thick boundary layer referred to by Cermak et al. (1970). A limitation of this facility is that only neutral, neutral/
slightly stable, and neutral/slightly unstable air flows can be simulat-
ed (Huitron, 1977).

**Research Questions and Hypotheses**

This study seeks to answer the following questions.

1. Can special groupings of buildings be used in urban areas to allow for an air flow pattern that reduces concentration of pollutants and create conditions conducive to thermal comfort within the areas
formed by two or more buildings?

2. To what extent do buildings designed for through-ventilation (porous structures) affect the potential for natural ventilation in other downstream structures in comparison to buildings not designed for through-ventilation (nonporous structures)?

3. To what extent do buildings designed for through-ventilation (porous structures) create within the spaces between them and on their lee side region stagnation areas, in comparison to buildings not designed for through-ventilation (nonporous structures)?

4. Do structures that create conditions for thermal comfort also create positive conditions for ambient air quality?

The following hypotheses were tested.

1. Structures that are a minimum obstacle to horizontal wind cause minimal impact on ambient air quality in the spaces between those structures.

2. Structures that are a minimal obstacle to horizontal wind allow for higher through-ventilation potentials in downstream structures.

3. Certain groupings of structures in urban areas, while increasing conditions for thermal comfort, may create regions of air stagnation in the space between them.

In addressing the research questions and testing the research hypotheses the study was subjected to several limitations which also served to narrow its focus and general application. First, the study was limited to evaluation of horizontal air flow characteristics and did not take into account vertical flow due to thermal forces and the urban "heat island" effect. Second, the study was limited to examination of
thermal comfort conditions on the basis of air speed as a single variable. Other variables such as air temperature, radiant energy and air humidity were not considered. Third, comparison of the wind tunnel observations with full scale data was not accomplished. However, all experiments were conducted in a manner that was consistent with current modelling theory and technique.

**Methods and Procedures**

The study was conducted in an "Environmental Wind Tunnel" facility shown in Figure 1, at the Cullen College of Engineering, University of Houston. It has 1.52 x 3.05 m in cross-section and is 20.73 m long, having an overall length of 36.58 m and a maximum cross-section of 4.57/4.57 m. The facility was designed for studying three-dimensional boundary layer flows and is appropriate for conducting model studies of flow over urban areas related to air pollution, modification of local environment, and structural-aerodynamic problems.

Special features of the wind tunnel include a filter system for open loop operation, an air bearing turntable and remote operation instrument positioner. Air is circulated with a 125 HP blower and is capable of moving 125,000 cubic feet per minute, thus simulating wind velocities up to 13.3 m/sec. Velocities as low as 0.5 m/sec. can also be obtained. In addition to the velocity and turbulence measuring equipment, smoke generator equipment for flow visualization studies and special gas analysers for concentration measurements are available. The facility is capable of simulating only neutral, neutral/slightly unstable, and neutral/slightly stable flows (D, C-D, and D-E, according to Pasquill's stability classes). From the graphs registered in the
recorder instrument, average points were determined and the average speeds calculated by using appropriate equations.

Three experiments were conducted. The first experiment was designed to investigate: (1) the flow characteristics in the lee side of two dimensional structures with different porosities; and (2) the flow characteristics in the lee side region of three-dimensional structures with different porosities and with different widths. The objective of this experiment was to assess the effect of porosity and volume of structures on air flow and concentration of contaminants in the lee side region of these structures.

The second experiment was designed to investigate the effect of porosity and distance between a series of structures on the flow characteristics in the lee side region and within the spaces between the following structures: (1) two-dimensional structures with equal porosity; (2) two-dimensional structures with equal porosity and the introduction of a nonporous structure; (3) three-dimensional structures with equal volume and equal porosity and the introduction of a nonporous structure. The objective of this experiment was to assess the through-ventilation potentials in downstream buildings and the potential for thermal comfort and pollution dispersion within the spaces between these structures and in their lee side region.

The third experiment was designed to investigate the effect of the distances between a group of structures on the flow characteristics in the lee side region and within the spaces between the following structures: (1) a group of three-dimensional structures with equal volume and different porosity; (2) a group of three-dimensional structures with
equal porosity and different volumes; and (3) a combination of 1 and 2. The objective of this experiment was to assess the potential for thermal comfort and air pollution dispersion within the spaces formed by a group of structures representing alternative development forms (e.g., building patterns, open space patterns, communication systems, etc.).

To stimulate wind flows encountered in urban areas, large roughness elements were placed upwind. As the existing floor roughness of the wind tunnel essentially simulates rural wind characteristics, adjustments were made to allow the velocity, turbulent intensity and stress profiles to be reflective of large roughness values. This allowed the region under study to lie outside the transition region. In all the experiments and for any wind direction model buildings with a minimum distance of 20 structure heights (x/H=20) covered the area upstream from the measurement points. Concentration gas analysers were used for studying the concentration field and the readings were compared with air speed measurements for flow with the same axial direction of the background flow. Comparison of results were also made with smoke visualization.

**Definition of Terms**

**Background flow**: Velocity profile of the atmospheric boundary layer for flow approaching the study area (Figure 2).

**Boundary layer**: Region of the atmosphere where the wind flow is affected by the surface characteristics. A typical boundary layer for rural areas is about 200 meters thick. For urban areas it is about 400-500 meters thick, due to urban increased surface roughness.

**Cavity**: Region within a wake subject to a rotational and
reverse flow (Figure 2).

**Nonporous structure:** Structure that does not allow the wind to go through the surface or volume it constitutes, i.e., 00% porosity structure.

**Porosity:** Characteristic of a structure that allows the wind to go through it. It is the result of openings in the walls of the structures or of space left open under the structure (e.g., when pilotis are used). An example of porosity in nature is the tree, which has both types of porosity (through the leaves and under the canopy). The degree of porosity is a measure of the percentage of the projected surface that is open for air flow. In this study the porosity varied from 0 (zero) to 50 percent.

**Porous structure:** Structure that allows the wind to go through the surface or volume it constitutes (i.e., 00% porosity structure).

**Structure:** Any isolated building or group of buildings and/or urban furniture (including trees) that obstructs the wind path.

**Urban furniture:** Any object in an urban area that forms a space and defines boundaries among buildings, such as, benches, walls, shelters, vegetation (including trees), etc.

**Wake:** The region in and around a structure where the velocity profile differs from that of the background flow approaching the structure. May be two or three-dimensional in shape (Figure 2).

**Organization of the Remainder of the Study**

The remainder of the study is presented in four chapters. In Chapter II a review of literature pertinent to this study is presented. Chapter III contains an explanation of the research procedures including
the experimental apparatus, the research design and the methodological assumptions that limited the generalizability of the study. Experimental findings are presented in Chapter IV, and Chapter V contains the summary, conclusions, and recommendations. The study concludes with reference citations and appropriate appendices, containing all the tables and figures referred to in the main text.
CHAPTER II

REVIEW OF THE LITERATURE

This chapter presents a review of literature. The scope of this review encompasses three particular areas. First, models and indices of thermal comfort are discussed particularly with respect to the effects of air movement. Second, the general characteristics of existing pollutant dispersion models are outlined with emphasis on how they describe pollution concentration in the vicinity of buildings. Finally, building and building-related experiments using wind tunnel physical modeling are reviewed. Throughout, the shortcomings of previous studies are discussed as they relate to the subject of this research.

Models of Thermal Comfort and Pollution Dispersion

The relations between external weather and the microclimate of rooms and buildings were analysed by Sargent et al. (1974). They arrived at the general conclusion that the development of shelter is a natural adaptative process to escape temporary unfavorable environmental conditions, and that houses built by man are an artificial extension of his homeostatic system.

Through settlement patterns and house form, variables of the atmospheric environment are controlled to approximate to the greatest possible extent the desired levels for man's comfort, well-being and health. Many examples of traditional architectural design in various climatic zones displaying good environmental fit can be found in the literature (Aronin, 1953; Atkinson, 1953; Ferrari, 1957; Fitch, 1976;
Fitch and Branch, 1960; Freire, 1959, 1967 and 1971; Goldfinger, 1970; Knowles, 1974; Koenigsberger et al., 1974; Maggers, 1971; Moholy-Nagy, 1976; Rapoport, 1969; Rudofsky, 1964; Stein, 1977; Swanton, 1946 and many others). However, the same cannot be said for contemporary urban architecture, especially with respect to atmospheric aspects. Serious heat and air pollution problems have arisen in many contemporary cities, to the point of requiring comprehensive plans for maintaining the level of environmental quality expected today.

To understand the thermal equilibrium between man and his atmospheric environment and the operational principles for achieving air quality represent an important step in the planning process. These principles are discussed next, under "indices of thermal comfort" and "pollution dispersion models". Here special emphasis is given to ventilation.

Indices of Thermal Comfort

Thermal equilibrium between man and his environment is necessary for maintaining appropriate bodily functions and for keeping the temperature of the core tissues within a narrow range around 37 deg. C. This equilibrium depends on man's activities, acclimatization, clothing, etc., and is affected by environmental variables, such as radiation, air temperature, air motion and water vapor content of the air.

Part of the energy produced internally by man's metabolic process is always lost, thus establishing processes of heat exchange between man and his environment which balance the energy gained or lost due to atmospheric variables. The processes involved are the radiative heat exchange, convective heat exchange, evaporative heat
loss, and conductive heat exchange. They are indicated in the general equation of thermal equilibrium shown below, which expresses the steady state, disregarding the conductive process, since it is of small significance.

\[ M + C + R + E = 0 \]

where,

- \( M \) = metabolic rate (metabolism + work)
- \( R \) = radiative heat exchange
- \( C \) = convective heat exchange
- \( E \) = evaporative heat loss

Many biometeorological models have been developed (Bassikos, 1968; Fanger, 1970; Givoni, 1969; Kamon, 1975; Koenigsberger et al., 1974 and many others). These models combine in equation and nomogram from both biological and meteorological data. They attempt to describe from experimental observations how the ambient atmospheric environment acts on the human organism and affect its thermal comfort, well-being and health.

Kamon (1975) cites the following equation proposed by Belding for radiative and convective heat exchange and for evaporative heat loss:

- \( R = 11 \ (tw - 35) \), where \( tw = tg + 1.8 \sqrt{v^{0.5}} \ (tg - ta) \)
- \( C = 12 \sqrt{v^{0.6}} \ (ta - 35) \)
- \( E_{max} = 24 \sqrt{v^{0.6}} \ (42 - P_{wa}) \)

For clothed man (cotton shirt and trousers added),

- \( R = 6.6 \ (tw - 35) \)
- \( C = 7.0 \sqrt{v^{0.6}} \ (ta - 35) \)
- \( E_{max} = 14 \sqrt{v^{0.6}} \ (42 - P_{wa}) \)
where

R, C and Emax, in Kcal/h

tw = temperature of solid surroundings (walls) °C
tg = temperature of 6-inch black globe °C

ta = air temperature, °C

V = air speed, m/sec.

35°C = assumed skin temperature

42 mmHg = H₂O vapour pressure of wet skin at 35°C

Pwa = H₂O vapour pressure of air in mmHg.

Sargent et al. (1964) summarize the representative biometeorological indices and describe the characteristics of the indices expressed in meteorological terms (e.g., effective temperature, corrected effective temperature, temperature-humidity index, wet-bulb globe thermometer index, wind chill, and cooling power) and physiological terms (e.g., predicted four-hour sweat rate and heat stress index). Physical parameters on thermal comfort, including some of the indices referred to above and many others, are also discussed by Landsberg (1972) and Givoni (1969).

A human comfort diagram is proposed by Olgyay (1952) with dry-bulb temperature as the ordinate and relative humidity as the abcissa, within which zones of comfort are entered. It is shown in his diagram how ventilation and radiation affects these zones, according to which a higher range of temperature and humidity is acceptable as comfortable in well ventilated environs.

Bassiakos (1968) developed the Atmospheric Index, based on thermal measurements on clothed man exposed to actual environmental
conditions. This index combines the effect of temperature, humidity, wind speed, and radiation.

Fanger (1970) developed a series of thermal comfort diagrams, specially for the purpose of environmental engineering. These diagrams, derived from the comfort equations based on experiments using North Americans as subjects, combine: (1) ambient air temperature versus wet-bulb temperature with relative air velocity as a parameter; (2) ambient air temperature versus relative air velocity with activity as a parameter; and (3) air temperature versus mean radiant temperature with relative air velocity as a parameter. Many different forms of clothing and activities were considered in determining the diagrams.

Koenigsberger et al. (1974) suggest the thermal comfort zone by means of the effective temperature nomogram for persons wearing normal business clothing, valid for Singapore and Australia. Limits of comfort acceptable for other geographical regions are also indicated. In this nomogram the atmospheric variables are ambient air temperature (or globe temperature for the corrected effective temperature), wetbulb temperature and wind velocity.

Givoni (1969) developed the Index of Thermal Stress and, on that basis, proposed the Building Bioclimatic Chart. Wet and drybulb temperatures are the variables. Ventilation, as in Olgyay's nomogram, can increase the range of temperature and humidity that is acceptable as comfortable.

The limitations of these indices for describing environment-organism interactions are acknowledged by Sargent et al. (1964) and Landsberg (1972). Landsberg (1972) says that although restrictions on
the exact solutions for describing the interactions between atmospheric environment and man's physiological make-up do exist, such attempts can be useful in limited areas if one is aware of the limitations that curb the generalibility of these solutions. Among these limitations are the difficulties in modeling the weather realistically and in describing actual human reactions with man performing tasks in the real world.

It would seem, therefore, that the use of these models for geographical regions and situations other than those for which they were designed is unscientific and/or impractical. Yet, the effective temperature index has been widely used in places such as Brasil and in other tropical regions, where they probably do not apply. Also, Olgyay's bioclimatic chart, which was developed for healthy Americans, has been the basis for approaches to natural climate control in other regions. It appears that appropriate models need to be developed for these regions in relation to different purposes of the design process.

In almost all the models refered to wind speed has been an important variable for achieving thermal comfort within a determined range. Koenigsberger et al. (1974) cites 1.5 m/sec. as the higher limit for indoor thermal conditions. Other ranges are considered. Yet there have been few attempts to assess the thermal comfort conditions out of doors. Pennwarden (1973) cites the work of Gold, in Croydon, England, and the work of Siple and Passel in the Antarctic as representing the only available information on the subject. Another study was conducted in Houston, Texas (Hazard, Cech, and Hacker, 1975). On the effects of wind, the earliest systematic work was done by Admiral Francis Beaufort, FRS, whose scale of wind force, devised in 1806, is still in use, according to which
comfortable and annoying conditions can be identified (Figure 3).

Based on the Beaufort scale, the acceptable wind speeds in towns was studied by Penwarden, (1973). The effects of wind on people, with the object of establishing limits of wind speeds which are acceptable or unacceptable were reviewed and the wind forces were tabulated (Figure 4). He determined the comfort regions for shade and full sunshine by using M. A. Humphrey's equation for indoor conditions adapted for outdoor conditions, at Humphrey's own suggestion, by the inclusion of a factor for solar radiation. This equation involves relating the rate of heat production within the body to the rate of heat loss through clothing to the external environment. The equation is:

\[ T_b - T_a = \frac{M}{A_{Du}} R_b + K \frac{M}{A_{Du}} R_c + (k \frac{M}{A_{Du}} + S) \left(4.2+13u^{0.5}\right)^{-1} \]

where:

- \( T_b \) Body core temperature (37°C)
- \( T_a \) Air temperature, degC
- \( M/A_{Du} \) Metabolic rate of heat production per square meter of body surface, W/m²
- \( K \) Proportion of metabolic heat dissipated by means other than evaporation (about 0.8)
- \( R_c \) Thermal resistance of clothing, m² deg C/W
  (popular unit: 0.155 m² deg C/W)
- \( R_b \) Thermal resistance of body tissues, m² deg C/W
- \( S \) Solar heat input per square meter of body surface, W/m² (Maximum value about 120 W/m²)
- \( u \) Wind speed, m/sec
- \( (4.2 - 13u^{0.5})^{-1} \) Thermal resistance between clothing and surroundings, m² deg C/W
Penwarden (1973) analyses through tables and diagrams the thermal properties of clothing and the comfort conditions for strolling in full sun and in shade. He discusses the combined effect of air temperature and wind speed, with thermal comfort as a criterion and describes the increased uncomfortable conditions created in cold climates by increased wind speed. He also analyses the effect of windy conditions in the vicinity of buildings, especially tall ones, where the resulting speed may be four or five times greater than in a sheltered site and acknowledges the unpleasantness or even the danger in such a situation, in agreement with what has been described by Wise et al. (1965) and Davenport (1972). However, in many tropical and subtropical regions the cooling effect of the wind is welcome. Increased wind speed, then, may be an advantage rather than a disadvantage, but other effects not related to thermal comfort must also be considered. Penwarden's diagrams show, however, that the cooling effect is reduced for speeds over 5 m/sec (Figure 5). If this threshold is confirmed, there would be no advantage in creating windy conditions involving speeds higher than 5 m/sec even in warm, humid regions.

Davenport (1972) has suggested human comfort criteria for environmental wind conditions, such as those set forth in table 1, taking as reference the Beaufort scale and some other studies on wind conditions in pedestrian regions. His comfort criteria show that the tolerable wind speed is dependent on the metabolic rate of the individuals, that is, on their activities. In cold climates the problem of comfort is related to wind chill, which makes higher wind speed less tolerable. In warm climates, and especially in humid regions, it appears that higher
wind speeds would be tolerable, which differ from the limits proposed in Table 1. Davenport (1972) acknowledges this when he says that the acceptable rates of occurrence at which various discomfort levels arise are suggested only as illustrations and that "proper investigations are required to establish definitive values"; they should include: "(1) the greater sensitivity of infants and elderly people; (2) the acclimatization of people in different geographic regions; and (3) the seasonal variations in dress and activities".

Whether or not the air movement is desirable for thermal comfort can be identified after a process of analysis, such as that proposed by J. M. Evans (1972) in Figure 6. However, most of the models and criteria described can be used for describing comfort conditions, depending, as discussed, on the purpose of the analysis.

**Pollution Dispersion Models**

The diffusion process in the atmospheric environment has been described in many mathematical models to relate pollutant emissions to ambient pollutant levels, so as to predict: "(a) consequences of new pollution sources on pollutant levels and patterns; (b) effects of alternative in urban planning solutions on pollution levels; (c) evolving pollution patterns in an expanding city; (d) effectiveness of various control strategies to reduce pollution levels in an area; and (e) emergency curtailment measures to be taken during episodes of high pollution levels." (A Guide for Reducing Air Pollution Through Urban Planning, 1971).

Although a large variety of models has been proposed, depending on the quantity and type of data available, types of sources being
considered, and their purposes (whether for planning or emergency episod prevention), nearly all the urban air pollution models "have been based on the wellknown normal bivariate diffusion formula for the steady-state concentrations at points at the ground downwind of a continuous point source", as Lamb and Neiburger (1971) point out. The formula they cite is:

$$X = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \left[ \exp \left( \frac{1}{2} \frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2} \right) \right]$$

where

- $X$ - ground level concentration (g.m$^{-3}$)
- $Q$ - emission rate (g.sec$^{-1}$)
- $h$ - source height (m)
- $y$ - lateral distance from the plume axis (m)
- $\bar{u}$ - mean wind speed (m.sec$^{-1}$)
- $\sigma_y$ and $\sigma_z$ - variances of the concentrations about the plume axis

They also cite the following assumptions made in deriving the formula: "steady state conditions, no spatial or temporal variations in the wind or atmospheric stability, no upper level inversion, no deposition of the contaminant or chemical reactions between it and other substances, and continuous point sources emitting at constant rates".

Another assumption is that the plume spread has a Gaussian distribution, both in the vertical and horizontal directions and perpendicular to the wind (Seinfeld, 1970; Turner, 1970).

The methods to determine pollution concentrations differ in the way in which the empirical standard deviations, $\sigma_y$ and $\sigma_z$, are determined (Seinfeld, 1970). They vary with the turbulent structure of the atmos-
phere, height above the surface, surface roughness, sampling time over which the concentration is to be estimated, wind speed, and distance from the source (Turner, 1974). Turner proposes two graphs for determining $\sigma_y$ and $\sigma_z$ as a function of six stability classes (A, B, C, D, E, and F), where class A is the most unstable and class F the most stable one. Turner (1974) points out that these methods will give representative indications of stability over rural areas, but are less reliable for urban areas, because of the city's larger surface roughness and heat island effect upon the stability regime over urban areas.

Formulas have been used by Christiansen and Porter (1976) and Christiansen (1976) for calculating the standard deviation $\sigma_y$ and $\sigma_z$, based on seven stability classes and as a function of wind distances, which give the same results as Turner's tables.

Seinfeld, in 1970, presented a summary of some of the most important urban atmospheric diffusion models that had been proposed until then.

Study of air pollution dispersion in the vicinities of buildings or within a group of buildings is complicated by flow characteristics that are very difficult to model mathematically; moreover, existing models do not apply in such cases because the model assumptions are contradicted. The investigation of these problems relies on physical modeling in wind tunnel facilities, as described later in this chapter. An important case is, for example, that of effluent from a chimney situated on the lee side of an obstacle which is carried very quickly to the ground if the chimney top is in the wake. When the effluent enters the wake of a building, or a group of buildings, "...there may be residual
pollution from previous whiffs when a whiff descends, and the real problem of building wakes lies not in the high maximum concentration experienced but in the fact that often there are regions such as courtyards from which the pollution is never completely cleared even though it arrives in gusts or whiffs" (Scorer, 1972). Once a chimney effluent enters the wake of a building, it means that it can enter the windows. The same conclusion can be drawn when pollutants emitted from automobiles or other sources are in the wake of a building. It would seem that only the removal of the chimney or of the automobiles from the wake would change this pattern. However, it is possible to alter the pattern if wind is allowed to enter the wake through porous elements.

**Experiments With Wind Tunnel Physical Modeling**

Flow patterns inside buildings and around isolated buildings or groups of buildings have been simulated in wind tunnel facilities (Caudill et al., 1951; Caudill et al., 1952; Evans, 1972; Givoni, 1968; Givoni et al., 1972; Reed, 1953; Smith and Wilson, 1978; Wise et al., 1965; White, ND), and the effect of flow patterns on diffusion of contaminants has been studied (Cermak, 1977); Hoydish et al., 1974; Robins et al., 1977 and 1977).

It has been found that the air flow pattern through a building depends on several factors, among them the location and type of inlet openings, direction of incoming air, distribution and characteristics of the partitions (Caudill et al., 1951, 1952; Evans, 1972; Givoni, 1968; Reed, 1953), as well as on location and special characteristics of landscape elements around the building, that can facilitate natural ventilation or work as a barrier against air flow (White, ND).
The basic patterns of wind flow around buildings have been determined (Evans, 1972). It was found that the downwind extent of a turbulent zone depends on building size, shape, type and slope of the roof, but is unaffected by wind velocity.

The plume dispersion in the vicinity of a surface mounted cube has been investigated (Robins et al., 1977 and 1977). The authors found that: (1) the highest concentration was obtained when the source (a low level point source release) was in the rear face of the building, and the lowest when the source was in the upstream face of the cube; (2) for a high level point source, material released from the downstream face tends to be trapped beneath the mixing layer leaving the rear edge of the roof and is rapidly mixed throughout the entire extent of the wake, while material released from the upstream face is swept over and around the building and then thoroughly mixed in the building wake. The authors say that the effective height of the plume will be greater in the latter than in the first case and that the plume extent will be also greater so that the virtual origin will be further upstream of the body. A study in Israel (Givoni, 1968) has determined the internal air speeds and flow directions in the center block of a group of three blocks, as well as in one block of an arrangement with alternate restrictions of the wind flow, for three different wind directions, and in rooms surrounding a rectangular court.

In another Israeli study the effect of high rise buildings in shaping the wind environment near the ground in an urban layout was investigated (Givoni et al., 1972). The objectives of the study were to determine: (1) the possibilities of ventilation within the building and
open spaces; and (2) the possibilities of reducing air pollution from vehicles (air pollution concentration). The author summarizes the effect of high rise buildings among low-rise ones as follows: higher speed air is brought down from the level above the built-up area to the level near the ground; the average speed near the ground is increased; vertical mixing of the air is increased; as a result of different combinations of locations, the flow near the ground can be modified, reversed or strengthened. Givoni et al. (1972) say that this pattern has a decisive influence on the dispersion of air pollution from motor vehicles, since the resulting agitated flow contributes to the mixing of clear upper air with the contaminated lower air. This is in agreement with studies of pollutant dispersion and flow patterns within an idealized model city (Hoydish et al., 1974), where it was found that a strong shear layer formed above the mean roof plane tended to trap pollutants below this level. The presence of high rise structures, the authors say "would change the pattern and cause pollutant dispersion due to corner vortices that rise above the mean roof plane". This reduces concentration at or below the mean roof plane at all points downwind. They conclude that "a number of very large scattered high rises may ventilate a city more effectively than either uniform low rises or high rises arranged in pyramidal fashion, like a downtown area of most cities".

The effect of tall buildings in mixed developments has also been examined by experiments by the Building Research Studies at Garston (Wise et al., 1965), applicable to air flow through urban areas. The pattern around parallel rows of similar building models follows the patterns described elsewhere, with vortex formation between the
buildings. The study of a slab block considerably higher than surrounding buildings shows a wind speed increase near ground level in the windward surface of the slab in relation to the undisturbed flow for the same height. In this latter case, speeds in the area downstream of the slab do not reach values as high as those at the sides and to windward, and a secondary flow (returning) with a direction opposite to the undisturbed flow is registered at levels near the ground. Increase of air speeds in some areas within the buildings have been cited by the authors as creating uncomfortable thermal comfort due to the chilling effect of wind in cold climate. Similar wind flow characteristics have been reported by Koenigsberger et al. (1974), related to studies in Australia, which produced the surprising result that if a low building is located in the wake of a tall block, the increased height of the obstructing block will increase the air flow through the low building in a direction opposite to that of the wind. In this case the secondary flow (returning flow) would pass through the buildings.

Smith et al. (1978) studied the airflow within rectangular walled enclosures whose dimensions in plan were varied, the heights of walls being held constant. They found that: (1) as the length of the models increases, the average velocity within the enclosure first climbs to a local maximum and then drops significantly before finally increasing again at large spacings, with the conclusion that, over a considerable range of sizes, shelter can only be increased by enlarging the space; (2) a wide enclosure is able to provide good protection from the wind over a larger range of lengths than a narrower one, although it still produces relatively windy conditions when it is about twice as long as
it is high, no matter how wide an enclosure may be; (3) for a length/height (L/H) ratio of less than about 5.5 a narrow enclosure affords better protection than a wider one, while for longer enclosures the reverse is true; and (4) higher velocities may be found in enclosures which are rotated to the oncoming flow than in those which face directly into it and they can exceed the undisturbed wind speed. In short, they found that the degree of shelter could be optimized by a correct choice of geometry. This study was interpreted in terms of comfort for cold regions and did not consider air quality as a criterion, which, in many cases, would require a level of wind circulation beyond the scope of the shelter.

Koenigsberger et al. (1974) report experiments at the Architectural Association Department of Tropical Studies, that yielded the following results. "If in a rural setting in open country, single story buildings are placed in rows in a grid-iron pattern, stagnation air zones leeward from the first row will overlap the second row. A spacing of six times the building height is necessary to ensure adequate air movement for the second row. Thus the 'five times height' rule for the spacing is not quite satisfactory. In a similar setting, if the buildings are staggered in a checker-board pattern, the flow field is much more uniform, stagnant zones are almost eliminated."

In a lecture at the University of Houston, Carmak (1977) showed a series of studies of air flow within urban areas, where trapping of pollutants occurs because of stagnation areas between structures. He also referred to a study for San Francisco, where special features in building design, such as the presence of *pilotis* (free-standing columns
or 'stilts'), created higher wind speed in some places, thus increasing discomfort due to the cold.

Smoke visualization of wind flow around a group of buildings, by this investigator, allowed determination of air-flow characteristics well in agreement with most of the previous works refered to above. However, a simulation of wind flow around high-rise buildings among rows of low-rise building demonstrated that a strong vortex is formed in the windward side of the high-rise buildings, which traps the pollutant released at low level between high and low-rise buildings. Higher air speeds were found in relation to parallel low-rise buildings, in agreement with the findings of Wise et al. (1965), probably due to the presence of stronger vortices.

Besides aspects of air flow among buildings, broader scale studies have shown that relationships exist between land-development patterns and air quality, leading to discussion of ways to enhance ventilation at a mesoscale so as to increase pollution dispersion and diffusion. A Guide for Reducing Air Pollution Through Urban Planning (1971) reports studies in Hartford, Chicago, Seattle, and Prince George's Montgomery Counties, in Maryland, where, in general, it has been demonstrated that the land use options considered in the alternative plans with the presence of green areas adjacent to pollutant sources resulted in lower apparent pollution concentration, both because the vegetation acts as a filter for pollutants and because the open spaces created greater opportunity for through ventilation in urban areas. Thus it was concluded that "(While) the research is still inadequate, it does appear that the use of a regional open space system to help disperse pollutant
can be of significant value". The study stresses, however, that it is very important to establish the correct location and size of open spaces.

The importance of green open spaces in urban areas has been widely referred to in the literature, from the viewpoint of both thermal comfort and pollution reduction (Peterson, 1971; McHarg, 1969; Whitehead, 1976; Cech, Weisberg, Hacker, and Lane, 1976; Bryson and Ross, 1972; Hadar, 1970).

From the foregoing reports one can conclude that the arrangement of buildings with respect to winds produces significant changes in the undisturbed flow which may or may not create adverse conditions in urban areas from the viewpoint of thermal comfort and ambient air quality.

Pollutants emitted from local sources in urban areas (e.g., building roof vents and automobiles) can be trapped within buildings and conveyed into windows, doorways, and air intake systems. Heat also can be trapped at lower levels by the vortex formed at the roof top under conditions of air stagnation between buildings, thus affecting thermal comfort in living spaces through increased air temperature and reduced wind speed. In urban climates this effect is negative, thus causing more heat stress than in undisturbed situations. During cold seasons, the effect on comfort would be beneficial if the heat trap is not accompanied by trapping of particulates and gases noxious to health.

Discontinuity of street canyons, especially with green areas located conveniently among built-up spaces, has been suggested in order to deal with pollution caused by moving sources (Peterson, 1971). The green areas would perform the following functions (Peterson, 1971):
(1) by varying the building density and amount of green areas, the urban heat island can be controlled to some extent. In warm climates a heat island intensity can be reduced by interspersing with green areas and shade trees, and in this way the terminal stress can be reduced during extended hot periods; (2) trees, especially conifers, efficiently remove some pollutants from the air that passes through them. They can act as a filter by absorption of some pollutants by the leaves and can increase the dilution of pollutants when they are placed between sources of pollution; and (3) since trees also inhibit noise from passing through them, shelter belts along the edge of major highways can greatly improve the noise environment of nearby living spaces.

However, it has been suggested that in the presence of moving urban pollution sources, in areas covered with dense groups of trees, pollutant trapping can occur when cars are actually below the canopy (Whitehead, 1976).

In conclusion, it seems that there is common agreement regarding the importance of air movement around buildings in urban areas both for the achievement of thermal comfort and favorable levels of ambient air quality. However, there is an apparent lack of definitive evidence upon which to establish a comprehensive set of design guidelines that would enable appropriate consideration of these parameters in the planning and design process. This study seeks to extend the current knowledge about air movement in urban areas and partially addresses the joint problem of achieving favorable thermal comfort and ambient air quality conditions in outdoor spaces around buildings. Specifically this study is an attempt to give a more complete assessment of the effects of air movement around buildings on the joint problem than provided by similar studies (Givoni et al. 1972) by measuring pollution concentration in addition to wind speed and direction. In comparison to the literature reviewed, this study is also unique in addressing the potential for through-ventilation in buildings situated in high-density urban areas by accounting for the effects of porosity of upwind structures, or sets of structures, on both thermal comfort and pollution dispersion around downstream structures.
CHAPTER III

RESEARCH PROCEDURES

In this chapter the methodology used in the study is described in detail under the following headings: (a) experimental apparatus; and (b) research design.

Experimental Apparatus

All the experiments described in this study were conducted in the "Environmental Wind Tunnel" facility shown in Figure 1, at the Cullen College of Engineering, University of Houston. It is 1.52 x 3.05m in cross-section and is 20.73m long, having an overall length of 36.58m and a maximum cross-section of 4.57 x 4.57m. The air velocity is well controlled at speeds as low as 0.5 m/sec by the numerous screens, grids, and openings designed into the wind tunnel. Probes are moved inside the tunnel on a remotely controlled survey carriage, which is mounted in such a way as to minimize air flow disturbances. To produce a thick boundary layer and creating the wind profile encountered in urban areas, a barrier 0.06m high was placed across the width of the tunnel and at the beginning of the working area, and model buildings were placed in a random pattern upwind of the research area, as indicated in Figure 7. The length of the model buildings was 24 times the height of the larger models and about 63 times the height of the smaller ones.

A special source was built to simulate the street level emission of pollutants. It consisted of aluminum tubing perforated with small holes, all of equal diameter and emitting the same amount of gas.
Concentration distribution was checked in an undisturbed air using ethylene as a tracer and a Varian Aerograph, Model 940 gas chromatograph. The gas analyser was also used in most of the concentration experiments. The sampling stations were also of aluminum tubing with a 2 mm internal diameter, connected to the sampling bottles (250 cc in volume) by plastic tubing. The emission velocity of the sources was less than 0.05 m/sec. Ammonia gas was used also in conjunction with a special paint during some of the concentration experiments (concentration visualization). The paint changed color (red to yellow and purple) when contacted with ammonia gas such that regions of different pollutant concentration could be observed. The paint consisted of 10% of polyvinyl alcohol (DuPont ELVANOL 71-30), 25% of glycerine, and 65% of water as well as red, blue, and yellow indicator dye (1 mg for 250 mg of paint).

Two-dimensional and three-dimensional structures were used in the study, both with and without openings representing porous and non-porous building structures. The two-dimensional structures were of two kinds. One consisted of pieces of balsa-wood 1.6 mm (1/16") thick, 38 mm high, and 608 mm long, both without holes (non-porous) and with holes (porous) cut in six horizontal strips along the length of each piece, representing 10%, 30%, and 50% of its surface area. The non-porous structures are called a 00% porosity structures and the porous ones, 10%, 30%, and 50% porosity structures. The other kind of structures consisted of pieces of balsa-wood 3.2 mm (1/8") thick, 100 mm high and 400 mm long, with 00% and 30% porosity; in the latter, the holes were 36 squares representing 30% of the surface area. The three-dimensional
structures were also posous and non-porous, and also of two kinds. One kind consisted of 19 mm wide, 38 mm high, and 152 mm long volumes, being non-porous structures cut from pine-wood timber; and the porous ones were made of pine-wood 1.6 mm thick, with holes cut in six horizontal strips along the length of their front (windwards) and back (lee-side) surfaces, representing 30% of these surface areas (a 30% porosity structure). The other kind consisted of a 100 mm wide, 100 mm high, and 400 mm long volumes, made of balsa-wood 3.2 mm thick, with front and back surfaces without holes (00% porosity) or with holes cut in 36 squares equal to 30% of the surface area (30% porosity). The three-dimensional structures had basically H x H x H and H/2 x H x 4H volumes, with the height "H" of the models as the basic dimension. Besides the porosity incorporated in the structure walls, different kinds of porosity were obtained by elevating the models above the floor of the wind tunnel, or by changing the spaces between structures. Multiples of the three-dimensional structures were also considered, allowing changes in the width, height, and the length of the basic structure to be used in the experiments.

The wind velocity was measured by means of a Pitot tube (1.08 mm and 3.02 mm of internal and external diameter). The Pitot tube was connected, via a lineariser and an averaging network, to a strip chart recorder. The mean speed at any point was obtained by observing the average of the trace in the recorder. In all the measurements, the Pitot tube was oriented into the wind so all the wind velocity data are the axial component of the incoming flow. Reprentation of non-axial wind directions was obtained from smoke visualization.
Smoke for flow visualization was produced by an oil type smoke generator. Photographic records were made with a 36 mm Pentax camera using 28 mm, 50 mm, and 100 mm lenses.

**Research Design**

To test the research questions, three experiments were conducted. The first experiment studied the effect of porosity and volume of structure on wind speed and direction and concentration of gases within the structures' wake and cavity boundaries. Wind velocity measurements and smoke visualization procedures were undertaken, using the two-dimensional structures with 00%, 10%, 30%, and 50% porosities and the three-dimensional structures with 00% and 30% porosities, both on the floor and elevated from the floor within the working area. The length of the three-dimensional structures varied from H to 12H, and the width, from H/2 to 4H.

The second experiment studied the effect of distances between structures on wind speed and direction and concentration of gases within the structures' wake and cavity boundaries, as well as on through-ventilation potentials of downstream structures. Wind velocity measurements, smoke visualization, concentration measurement, and concentration visualization were undertaken, using three-dimensional structures with 00% and 30% porosities, on the floor and elevated from the floor of the wind tunnel's working surface. In each set of these experiments the structure volumes was held constant, with changes only in the porosity of one of the structures. Two combinations of structures were studied: One consisted of the combination of two structures separated by distances of 1H, 2H, 3H, 4H, 5H, and 6H (1, 2, . . . , 6 times the height "H" of the
basic structure), as shown in Figure 8. The other consisted of rows of 5 and 6 structures with each row separated by distances of 1H, 2H, 3H, 4H, 5H, and 6H (1, 2, . . . , 6 times the height "H" of the basic model, as shown in Figure 9.

The third experiment studied the effect of the density of a group of porous and nonporous structures on concentration of gases within the spaces formed between them and on their lee-side region. The structure characteristics, including the location of emission sources and sampling stations are shown in Figure 40, 41, 42 and 43. According to these figures, an incremental increase in density is obtained through an increment increase in the structures' height, the number of structures, or both. In this experiment, concentration visualization and concentration measurement were undertaken.

The validity and reliability of the particular experimental apparatus used in the research are described by Huitron (1977). Wind speed and direction, as well as gas concentration, were properly simulated for pollutant dispersion. The similarity criteria employed in order to adequately represent the dispersion and transport of pollutants are: (1) uniform geometric scaling, with ratio model to prototype from 1:400 to 1:1000; (2) meteorological conditions for neutral stability with moderate wind speed (Beaufort Scales 3 to 6) at the three meter elevation, and equivalent boundary layer heights from 100 to 400 meters; (3) Reynolds similarity achieved by using upwind roughness elements and a boundary layer trip (Huitron, 1977); and (4) neutral density source for emissions obtained by using ethylene gas as the pollutant. Only wind directions normal to the structures was simulated. The lack of availability of time and other resources precluded more comprehensive study.
CHAPTER IV

FINDINGS

This chapter presents and discusses the results of the experiments conducted in an environmental wind tunnel facility to test the research hypotheses in order to answer the questions posed in the first chapter. The data collected are organized in tables and figures, as follows:

1) all wind velocities measured in the experiments are presented in Tables 6 and 7 and/or are given graphically in Figures 17 to 29 and 45 to 47; (2) the pictures and diagrams resulting from smoke visualization studies are shown in Figures 11 to 17 and 30 to 34; (3) the data on gas concentration are set forth in Tables 4, 5 and 6 and in Figures 41, 42 and 43; and (4) the results of concentration visualization studies are shown in Figures 35 to 40.

Findings for Four Research Questions

and Brief Discussion

The effect of special groupings of buildings in urban areas on concentration of pollutants and on conditions of ambient thermal comfort in the vicinity of the buildings (Research question number one). The assessment of pollution potentials in the vicinity of buildings is dependent not only on the wind speed, but also on the flow characteristics around structures and within the space between structures, as well as on the location of emission sources, that is, whether these sources are inside or outside the cavity.

In the case of an emission source located inside the cavity the concentration of gases and particulates is a function of the air speed.
The effect of wind speed on dilution of a pollutant source within the cavity reaches the maximum and does not increase for wind speed higher than a given value. This phenomenon was found in a case study (unpublished paper) conducted in the environmental wind tunnel of the University of Houston, under the guidance of Dr. Frank Worley, Jr., Professor of Chemical Engineering, and with the participation of Arturo Gallegos, Javier Huitron and this investigator. This study was contracted by the St. Paul-Minneapolis Airport authorities for testing the effect of alternative development models on air pollution at particular points of the airport, especially in pedestrian areas.

The effect of wind velocity on thermal comfort is twofold: in cold climates, increasing the air speed may be undesirable because of its cooling effect, although in warm climates air speed is an asset, especially in humid regions. However, beyond a certain velocity adverse conditions may be created. In cold climates, better conditions for thermal comfort are encountered when the air velocity is minimal or close to zero. These conditions are found in sheltered precincts, such as in the lee side region of nonporous and low-porosity structures or within certain spaces between buildings.

Figure 10 presents some model combinations, and Table 2 shows the air velocities measured in the middle of the space formed by two structures and in the lee side of the downstream structure. The data suggest the following conditions pertained.

1. For ground level structures:

   a) when the upstream structure is a nonporous one, the flow inside the space between these structures is reversed and occurs at low
velocity relative to the mean stream, while the flow in the lee side region of the downstream porous structure is reduced; and

b) when the upstream structure is a porous one, the flow inside the space between these structures follows the pattern described above (a) at points near the ground; whereas at points with higher elevations, the air flow is in the same direction of the incoming flow, but at lower speeds relative to the mean stream.

2. For structures elevated from the ground:

a) when the upstream structure is elevated, the flow within the space between two structures and at points with elevations lower than H/3 (i.e., lower than the gap formed underneath the structure) reaches higher velocities than the velocity found in the background flow for the same elevation; and

b) when the downstream structure is elevated, the flow in its lee side and at points with elevations lower than H/3 reaches velocities about 20 percent lower or higher than the velocities in the background flow, even if the upstream structure is on the ground. However, reverse flow and lower velocities are encountered at the other points inside the cavity formed behind the structures.

Air speeds at points near the ground level determine comfort conditions in streets, parks or passage way areas, where people stay for certain periods of time. The above statement leads to the conclusion that in warm climates comfortable conditions are enhanced by elevating the structures above the ground. By contrast, this situation is highly undesirable for living conditions in cold climates. An increase in wind velocity may also be a drawback in warm climates when the incoming
velocity is above 5 m/sec because the convergence effect due to structures can result in ground level velocities greater than 10 m/sec. In contrast to the above convergence effect, flow in the wake may be greatly reduced, and thus reducing the cooling effect of the wind.

Figures 11 to 29 show the speed profiles and characteristics in downstream environs of porous and nonporous structures. The data collected to construct these Figures are available from the author or from Rice University, School of Architecture. These structures can be interpreted as isolated buildings or a group of buildings forming part of the city. Here the degree of porosity simulates windows or other openings in buildings or the space left between buildings. The data show how the wake of a structure can be reduced in size by allowing some air to enter underneath it, such as with the use of pilôtes, so creating better ventilation in ground precincts and allowing for better through-ventilation in downstream structures.

Other noteworthy features depicted in these figures are indicated below.

1. Points situated approximately in the middle of the wake and close to the ground level generally indicated lower wind speeds and higher smoke concentrations when the structure is porous and on the ground.

2. The two-dimensional structures studied (Figure 11) showed that the 10 percent porosity structure created lower wind speed in a downstream region than the other structures, and that more smoke was accumulated. The 30 percent structure region was located further downstream and was smaller in size, while the 50 percent structure indicated no
stagnant region. It seems that up to porosities of 30 percent, porosity increases smoke concentration, and that with porosities between 30 and 50 percent, porosity does not create a stagnant zone, because the air that enters through the porous elements minimizes the vortex flow created by nonporous structures.

The results presented in Figures 17 to 27 35, 41, 42 and 43 and Tables 3, 4, and 5 also show how the ambient quality is affected by various groupings of structures and by the characteristics and degree of porosity. Many features of the above figures and tables will be discussed in relationship to research question number two. However, for the purpose of the present research question, noteworthy features are summarized below.

1. The data in Figure 42 and Table 4 show that higher pollutant concentration and poorer ventilation occurs within the space between structures when density increases. This is the case when the wind is normal to the structures and the pollutant source is located inside the space bounded by these structures, as happens in the space where LS-2 is located. Within this space thermal comfort conditions are uncomfortable for warm, humid climates and favorable for cold climates. In Figure 40 the distance between structures is equal to H/2 in experimental run No. 9 and to H/10 in run No. 12. However, Figures 45, 46 and 47, and the figures resulting from smoke visualization, suggest that for distances between buildings greater than about 1-building height, ventilation is enhanced within the enclosed space. In this case air flow is diverted downwards from the downwind structure. The information presented above seems to explain the lower concentration found in
experimental run No. 7 in Figure 41. Air flow that penetrates the enclosed space is likely to help dilute pollutants. The figures cited above also suggest that this critical distance between structures may be reduced if the structures are porous.

2. The data in Figure 41 and Table 3 show that higher air speeds and lower pollutant concentrations occur near the ground level and in the windward side of a high-rise structure located in a group of low-rise structures each with the same height.

3. The data for the building grouping studied showed, for ground level sources located as indicated in Figure 35 and 40, that the lower the porosity the better the air quality within the space between the structures or downstream of these structures. However, for other source locations and when the plume is captured (i.e., for different distances upwind and for different elevations), the resulting wake concentration will approach the plume concentration. In this case, higher concentrations within the enclosed spaces may occur.

The effect of buildings designed for through-ventilation, in comparison with buildings not designed for through ventilation, on natural ventilation in downstream structures (Research Question number two).

The curves in Figures 45, 46 and 47 show the ratio between the average speed of the outflow air and the speed of the background flow at the same elevation, for different distances between structures. In these figures, as in all the others, these distances are given in terms of the model height "H". The outflow air was measured across the openings (windows) located on the lee side wall and close to the center of
the structure (Figure 44). At the points of measurement the effect of the upstream structure on the readings is at a maximum. The graphs on the left side are for 30 percent porosity structures in all rows. The graphs on the right side are for zero porosity structures in the first row and 30 percent porosity structures in the other rows. In these graphs the curves for the second row are parallel to the curves for the first row, between 6 and 10 d/H. This is contrary to what should be expected, that is, a steep curve for the second row. It appears that at a certain distance d/H (probably equal to 20) the curves for all rows are superimposed.

The main features of the curves may be described by the following points.

1. The ratios of average speed to background speed behind the second and third rows downwind are reduced in relation to the ratios behind the first row. For distances greater than 5 or 6H, this ratio is higher behind the second row when the first row is of zero porosity than when it is of 30 percent porosity.

2. The ratio of average speed to background speed found behind the first row is almost the same whether the first row is of zero or 30 percent porosity.

3. Up to a distance equal to 5 d/H, the curves start with lower speeds in the presence of zero porosity structures than when all the structures are of 30 percent porosity. The curves are steeper when a nonporous structure is in the first row.

4. In all rows, the lower the elevation of the point of measurement, the higher the ratio average of speed to background speed.
However, the average speeds at these points are the same (Table 6). The lower reading of the background speed at lower altitudes resulted in higher ratios at these elevations (Table 7).

The effect of porous structures, in comparison with nonporous structures, on ambient air quality in windward and lee side areas.

(Research question number three). Figures 35 to 40 show the effect of porous and nonporous structures on the concentration of contaminants at ground level.

When the sources of gas are outside the structures (Figure 35), as in the case of an expressway passing in front of a group of buildings or a row of trees, higher dilution occurs when all the structures are porous. On the other hand, porous structures cause higher concentration of gases within the spaces between structures in comparison with the concentration that results when the first row is nonporous. This is because the air that enters the space through the porous elements distributes, more or less equally, the amount of gas emitted to the whole area downwind. The concentrations are higher near the source and decrease with the distance downwind, both when the porosities are on the walls of the structures or result from elevating the structures above ground. For the porosities studied, the flow is diverted by the structure, causing the gases to spread to both sides of the structure. This diversion may result in air with lower pollutant concentrations entering the wake and thereby result in lower concentrations on the lee side area. As expected, the concentration decreases from the first enclosed space to the third due to dilution and dispersion as the air passes through each structure.
With the introduction of a nonporous structure in the first row, the gas distribution pattern changes. Here, flow diverts to both sides and upwards and therefore, as noted above, lower concentrations of gas enter the building wake. An exception occurs at some locations at the corners of the structure. Much higher gas concentration occurs in the vicinity of the line source and beside the building group.

When the sources of gases are within the cavity, the effect of porous structures in comparison with nonporous ones is different (Figure 36). In a row of only porous structures, the concentration inside the enclosed space where the line source is located was found to be lower than the concentration resulting from the presence of a nonporous structure. Locations of high concentration are found very near to the lee side wall of the porous structure. This is a function of a series of small vortices formed at the corners of the openings due to outflow air. The pollutant gas concentration is almost uniform throughout the ground level and behind the first row. As expected the gas concentration decreases downwind within the spaces between the second and third and the third and fourth rows of structures. With a nonporous structure in the first row, the concentrations are much higher in its lee side and much lower within the second and third enclosed spaces, as hence the air and gases move sideways and upwards. However, areas of higher concentration are formed at the corners of the downwind structures.

In a grouping of buildings as in Figure 37, much the same pattern occurs for a gas source in the second enclosed space. The concentration resulting on the lee side of the porous structure in the second row is much lower than the concentration in the same region when
a nonporous structure is introduced. The third enclosed space is not affected by the presence of a nonporous structure, as air goes through the third row in both cases. Figures 38 and 39 show how a combination of porosities and structure heights can change the pattern. The combinations a and b in Figures 38 and 39 show that a taller structure in the third row can cause, near the ground level, a strong reverse flow (a) that dilutes the gas within the cavity formed behind the first row and on the lee side of the taller structure. With the combination b much higher pollutant concentrations can be seen near the lee side wall (cavity) of the second row. In both cases, as in others, the gas does not penetrate the third enclosed space, except at some corner locations at the third and fourth rows. The presence of a second tall structure in the first row (combination c, Figures 38 and 39) changes the patterns noted above and results in much higher pollutant concentrations being formed on the lee side of the second row. It seems that the presence of porous structures in the second row would create a pattern similar to a in Figures 38 and 39, and that a higher volume of air would help to dilute the gases released within the spaces between buildings. In this case, however, the concentration inside the first enclosed space should increase.

Figures 30 to 34 (smoke visualization studies) exhibit the same patterns of Figures 35, 26 and 37, for different distances between structures. Hence higher smoke concentrations are encountered within the first enclosure when the smoke probe is located within this space. Much higher values were found when the first row is nonporous than when it is porous. The smoke concentration decreases as the distance between
structures (rows) increases, as more air can penetrate the space. Similar results were found in the concentration visualization studies. The pattern inside the third enclosure does not change whether the first row is a porous or a nonporous structure.

A noteworthy feature of Figures 30 to 34 is that higher concentrations of smoke and gas are found close to the ground about the center of the space between structures when the first row is a porous structure than when it is nonporous. Probably this is due to the stagnation formed when the return flow encounters the flow that passes through the porous elements. At this particular location thermal comfort is reduced and the possibility of pollutant concentration is increased. This phenomenon does not happen however, when the porosity results from elevating the structure above ground, as the air passing beneath the structure is at much higher speed (Table 2).

Measurement of gas concentrations (Figure 43 and Table 5) for a distance between structures equal to 2H (two-building heights) shows that the concentrations measured within the first space are higher when the first row is a nonporous structure than the concentration resulting when it is porous. Concentrations within the other spaces are about the same in both cases, whether all the sources, or only the first one, are connected.

Figure 41 and Table 3 show how a pattern with tall and short structure can help reduce the concentration in all the spaces between structures. The data suggest that the use of structures with different heights can be conducive to better air quality, and probably to thermal comfort conditions in warm and humid climates, as air speeds from higher
altitudes are diverted downwards. When the sources are outside and up-stream of the structures, however, this pattern of air circulation may cause undesirable gas concentrations at ground level.

Concentration measurements made for a group of structures representing increased density through increased structure height (Table 4 and Figure 42) showed that the concentrations of gases are: (1) not affected in sampling station one; (2) increased at sampling station two as the densities increase; and (3) decreased in sampling station three, four, five and six, again as densities increase. It seems that the increased concentration at SS-2 is due to increased structure height. This reduces the air flow into the precinct and pollutants are trapped as a consequence of strong vortices formed at the roof top and at the corners of the space. The reduction in concentration at SS-3, SS-4, SS-5 and SS-6 occurs because the flow is progressively diverted sideways and upwards as building density increases. Some air flow enters the spaces between structures where LS-4 and LS-5 are located and carries the gases forward. No sampling station was located near LS-4 and LS-5, but it appears, based on concentration visualization studies, that lower concentrations would occur with higher densities for the same volume of gas emission rates at LS-4 and LS-5. In this case, as in all others, as land-use density increases, pollution problems seem to be exacerbated when pollutants are released at increasing rates.

**Conditions for thermal comfort versus ambient air quality**

(Research question number four). The figures and tables previously cited show that structures that create favorable conditions for ambient air quality are not always conducive to thermal comfort. It was shown,
when the gas source is located inside the cavity of a structure, that most of the structures that create conditions conducive to thermal comfort in warm and humid climates create equally favorable conditions for ambient air quality. However, the characteristics leading to thermal comfort in cold climates are also favorable to air stagnation and thus higher gas concentrations. When the source is outside, the reverse is true in most of the cases studied for precincts situated inside the spaces formed by a group of structures.

Taking the thermal comfort conditions for warm and humid climates as a criterion (where ventilation is considered an asset) for conforming or rejecting the research hypotheses, the foregoing shows that the data: (1) supported the first research hypothesis for ground level precincts situated within the spaces formed by two or more structures, when sources of pollution are inside these spaces; (2) rejected the first research hypothesis for ground level precincts situated within the spaces formed by two or more structures, when the sources of pollutants are outside and upstream of these spaces; (3) supported the second research hypothesis when the space between structures is smaller than 6 times the height of the structure; and (4) the third research hypothesis was not confirmed or rejected in any definitive manner, as the magnitude of the effect was found to be unimportant in many cases.

On the basis of the foregoing the answers to the research questions may be summarized in the following manner.

1. Special groupings of buildings in urban areas may cause an air flow pattern within the outdoor spaces (i.e., precincts between buildings) that reduce pollutant concentrations and create conditions
for thermal comfort.

2. Buildings designed for through-ventilation (porous structures) allow a higher potential for natural ventilation in other downstream structures when compared with buildings not designed for through-ventilation (nonporous structures). This is particularly significant when the distance between buildings is up to five or six-times the building heights. For distances smaller than two times the building heights, this effect is even more significant. For distances longer than six times the building heights, the effect is minimal.

3. Pollution concentration on the lee side region and within the space formed by two or more buildings designed for through-ventilation (porous structures) is likely to be lower, on the whole, than when these buildings are not designed for through-ventilation (nonporous structures). This applies when emission sources are located inside the spaces between buildings or inside the wake formed by these buildings. If the sources are outside and upstream, the reverse is true.

4. Structures that create conditions conducive to thermal comfort almost always create positive conditions for air quality.
CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Many socio-economic advantages have led to concentration of economic activity in cities, that, in turn, have directly contributed to forms of pollution, especially air pollution, and to increased thermal stress. Air pollution and thermal problems in cities can be controlled to a certain extent through building design and city planning as improved environmental quality can result from changes in urban development patterns and building forms.

In this research, many examples of architectural adaptation to climate and efficient control of the variables of the atmospheric environment to achieve thermal comfort and ambient air quality were analysed. The models of thermal comfort and pollution dispersion showed that ventilation is the single most important controllable element of the atmosphere in urban and building design. Especially in warm and humid regions, it is the key component in the dispersion and dilution of pollutants generated by urban activities and in the achievement of thermal comfort within and around buildings.

The purpose of this study was to provide building and urban designers with information about how efficient cross-ventilation and significant dissipation and dilution of pollutants can occur for selected spatial organizations of urban areas and for particular building patterns.

A physical modeling technique using an environmental wind tunnel
facility was chosen to assess the flow characteristics through and around buildings and within spaces formed by two or more buildings. For this modelling the environmental wind tunnel facility at the University of Houston, Cullen College of Engineering was used. The facility is capable of simulating a three-dimensional atmospheric boundary layer appropriate for conducting studies of air flow related to air pollution, modification of local environment, and structural-aerodynamic problems within urban areas.

Three experiments were conducted to investigate the influence of wind speed and direction on the pollutant concentration distribution on the lee side region of isolated porous and nonporous structures and in the area bounded by two or more structures, as well as the through-ventilation potentials of downstream structures as a function of the distance and porosity of upstream structures.

Thermal comfort for warm and humid regions and ambient air quality served as the criterion for assessing the advantages and disadvantages of the models that were studied. It was shown that for cold regions the assessment would be rather different with respect to thermal comfort.

The study was intended to answer the following four research questions.

1. Can special groupings of buildings be used in urban areas to allow for an air flow pattern that reduces concentration of pollutants and creates conditions conducive to thermal comfort within the spaces formed by two or more buildings?

2. To what extent do buildings designed for through-ventilation
(porous structures) affect the potential for natural ventilation in other downstream structures in comparison to buildings not designed for through-ventilation (nonporous structures)?

3. To what extent do buildings designed for through-ventilation (porous structures) create stagnation areas within the spaces they form and on their lee side region in comparison to buildings not designed for through-ventilation (nonporous structures)?

4. Do structures that create conditions for thermal comfort create also positive conditions for ambient air quality?

The research questions required the testing of the following three hypotheses.

1. Structures that are a minimal flow obstacle to horizontal wind cause minimal impact on ambient air quality within the area they bound.

2. Structures that pose a minimal obstacle to horizontal wind allow for higher through-ventilation potentials in downstream structures.

3. Certain grouping of structures in urban areas while increasing conditions for thermal comfort may create regions of air stagnation within the area(s) they bound.

To assess both thermal comfort and ambient air quality in the experiments, wind velocity measurements, smoke visualization and concentration measurements and visualizations were undertaken.

The following results were obtained from the experiments.

1. The first research hypothesis was confirmed when sources of pollution were located inside the space between structures, so that structures that present a minimal obstacle to horizontal wind are likely to have an effect on ambient air quality of ground level precincts
situated within the area bounded by two or more structures if the pollutant sources are inside these areas.

2. The first research hypothesis was rejected when sources of pollution were located outside and upstream of the spaces. Experiment showed that structures that present a minimal obstacle for horizontal wind are likely to have a greater effect on ambient air quality in downstream and ground level precincts, situated within the space formed by two or more structures, if ground level sources of pollution are outside and upstream of the space.

3. The second research hypothesis was confirmed when the enclosed length was less than 6 times the building height, so that structures presenting a minimal obstacle to horizontal wind allow for high through-ventilation potential in downstream structures. For spacings greater than 6 times the building height, a slight reduction in through-ventilation potential was found.

4. The third research hypothesis was neither confirmed nor rejected in any definitive manner, as the magnitude of the effect was found to be unimportant in most cases.

Conclusions and Design Principles

The findings of this study led to the following five conclusions.

1. Pedestrian precincts situated within the space formed by porous structures are subject to much better thermal comfort and ambient air quality conditions than when the spaces are bounded by nonporous structures, if ground level sources of pollution are located within these spaces and the wind is normal to the structures. However, approximately in the middle of the spaces bounded by porous structures of up to 30
percent porosity a significant stagnant zone may be formed, which may also create favorable conditions for accumulation of contaminants and poorer thermal comfort conditions.

2. Higher pollution concentration may occur within the spaces formed by two or more porous structures than when these spaces are formed by nonporous structures. This only occurs if ground level sources of pollutants are located outside and upstream of these spaces and the wind is normal to the structures. Conditions for thermal comfort are poorer in the spaces formed by nonporous structures.

3. Porous structures are much more effective than nonporous structures for creating through-ventilation potentials in downstream structures when the downstream structures are of the same height and at distance downstream of up to 6-structure height. This applies when wind is normal to the structures. At distances over 6-structure height and beyond the third row of structures downstream, through-ventilation potentials are not significantly affected by the porosity of the first upstream structure.

4. The increase of the height of structures forming an enclosed space may enhance pollution accumulation at ground level, if sources of contaminants are located within the space, the roof tops are at the same height, and the wind is normal to the structures. If the downstream structure's roof top is higher, the accumulation is lower and thermal comfort conditions are enhanced.

5. Increasing a structure's height will reduce the pollutant concentration on its lee side region if the emission sources are located in this region, that is, the pollutants are distributed in a larger
volume of air in the wake resulting in a homogeneous gas distribution on the lee side of the structure.

For reasons cited earlier, the influence of wind speed around structures and within the spaces formed by two or more structures was taken as a criterion for assessing thermal comfort for warm and humid regions. According to this criterion, the higher the wind speed the better the thermal comfort conditions. However, other effects upon man and his environment may be created by very high wind speeds, such as the raising of dust, dry soil and loose paper and the difficulty encountered in walking steadily.

From the above criterion and the research findings, it seems also that conditions conducive to thermal comfort always lead to better ambient air quality for warm and humid regions. One exception exists in pedestrian areas located in the spaces between structures when ground level sources of pollutants are outside and upstream of these spaces, and the wind is perpendicular to the structures. In this case contaminants may penetrate these spaces through the porous elements and may accumulate there, as well as in other downstream areas between structures. Another exception exists when a tall structure is located downstream of a short one. In this case it is possible for polluted air, resulting from elevated upwind sources, to be diverted downwards and accumulated in the areas bounded by these structures, that is, within the cavity.

However, in the real world pollution sources are seldom located just inside or outside spaces. Pollutant emissions occur as a result of man's activities at many points within the urban areas, although the
amount of contaminants varies for different city zones. Better thermal comfort and ambient air quality conditions are likely to be created within urban areas when the whole city allows for good ventilation, that is, when the city porosity is maximized and open spaces are left within built-up areas.

Desirable conditions for adequate thermal comfort and ambient air quality can be achieved by following several design principles (Figure 48).

First, through-ventilation in downstream buildings may be maximized if they are located at a distance equal to or greater than 6 building heights from upstream structures. This distance may be reduced if *pilotis* are used, as the wind is diverted downwards, passes through the gap created at ground level and reduces the wake length. This distance between structures may probably also be reduced in a group of buildings if a larger number of spaces are left between upstream rows of buildings thus creating a high-porosity set of structures. However, drag forces, friction, and upwards and sideways wind diversion due to the structures will reduce air speeds further downwind, such that conditions for thermal comfort and through-ventilation deteriorate.

Second, appropriately located tall buildings amongst short ones will ventilate pedestrian precincts more efficiently than when all the buildings have the same height. This will result in better conditions for thermal comfort and ambient air quality in these precincts if the pollutant sources are located within them. If short and tall building groupings and the porosity of these buildings are not properly determined, negative conditions around some buildings may be created. A non-
porous short building located between two tall buildings may enhance ventilation within the downwind space bounded by the buildings and create a stagnant air zone within the upwind space and near to the ground level. However, a porous short building in a similar pattern may enhance ventilation in both spaces, as a reversing flow is likely to penetrate the space upwind. The effectiveness of these solutions in creating environmental quality depends on the location of pollution sources (whether they are within just one space or outside and upstream of the space) and on the activities taking place in these precincts.

If pedestrian precincts are located in the upwind space (such as a park for long-term resting) and the pollution sources are within the downwind space (expressway passing through a downwind space), the pattern with nonporous short buildings seems to create better ambient air quality conditions in the park than in the pattern with porous ones. But poorer ventilation may also result in the park. Thermal comfort conditions may be enhanced if the tall upstream building has some porosity at ground level. On the other hand, poorer air quality may result if the plume from pollutant sources at higher elevations is captured by the group of buildings. It is expected that a pattern with tall buildings downstream from short buildings will divert polluted air into ground level spaces. In this case a group of buildings diverting the flow upwards and sideways would be preferable. However, in the real world and especially in urban areas, the wind blows from many directions and can change direction in a short space of time. Moreover, pollutants are likely to be released in many parts of the city and at different elevations. Therefore, reliable information about prevailing wind speed
and direction and the location of pollutant sources is necessary for
determining patterns that lead to environmental quality for all wind
and pollutant source characteristics.

Third, the velocity of wind flow immediately downstream from the
lee side windows of high-rise buildings designed for cross-ventilation
is likely to be the same at any window elevation. This observation
holds within the following parameters: 1) that, at all elevations,
both the windward and lee side windows are of the same size; 2) that
the windows are totally open to air flow without any obstructions to
the inflow air; and 3) that the wind direction is normal to the windows.
However, because of alterations to the inflow on the windward side
created by surface awnings (pivotal windows or shading devices), higher
outflow velocities will likely occur on the lee side of the building at
higher elevations. Conversely, reduction of inflow created by surface
awnings at lower elevations will likely result in decreased outflow
velocities immediately downstream of the lower lee side windows. It
appears that either windows that open completely or different partially
opening window designs for different elevations will lead to enhanced
through-ventilation.

In short, adherence to the following general principles related
to air movement is likely to enhance thermal comfort and ambient air
quality in urban areas situated in warm and humid regions.

1. Settlements should be constituted of buildings and urban furni-
ture patterns that permit horizontal wind to enter the living spaces.
Proper grouping of short and tall buildings, use of open spaces con-
veniently dispersed within the urban area, and choice of
urban forms that present minimal obstacles to prevailing winds will maximize enhancement.

2. Activities that produce larger amounts of contaminants must be located in such a way that pollution plume dispersions do not penetrate and accumulate within living precincts.

3. Buildings and urban furniture in cities, especially groups of trees, must have some degree of porosity near street environs where cars and pedestrians coexist so as to allow higher air speeds and adequate dispersion of pollution at ground level.

4. Shelter must be located between heavy-traffic streets or expressways and sites for long-term out-of-door activities (e.g., park) in such a way that the polluted air that passes through the former does not penetrate the space occupied by the latter. However, by adhering to this principle thermal stress in the park and pollution concentration in the expressway may be increased.

**Recommendations for Further Study**

Given the limitations of this study stated earlier, other studies should be undertaken before definitive design guidelines for achieving high levels of thermal comfort and ambient air quality can be established. Several important areas for further study may be enumerated.

1. An assessment, with variation in wind direction, of the effect of porous and nonporous structures on flow characteristics within the space that they form and on the downstream region of isolated structures.

2. An assessment of the effect of different urban patterns on air flow and concentration characteristics within pedestrian precincts,
taking into account the vertical thermodynamic forces and the horizontal wind forces, simultaneously.

3. Testing of critical space dimensions between tall and short structures that are conducive to both thermal comfort and ambient air quality conditions within the precincts formed by the structures.
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APPENDIX A

TABLES
### Units: Beaufort Number Temperatures 10° C

<table>
<thead>
<tr>
<th>Activity</th>
<th>Areas Applicable</th>
<th>PERCEPTIBLE</th>
<th>TOLERABLE</th>
<th>UNPLEASANT</th>
<th>DANGEROUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Walking fast</td>
<td>Sidewalks</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>2. Strolling, skating</td>
<td>Parks, entrances skating rinks</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>3. Standing, sitting -short exposure</td>
<td>Parks, plaza areas</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>4. Standing, sitting -long exposure</td>
<td>Outdoor restaurants, bandshells, theatres</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Representative criteria for acceptability

At lower temperatures relative comfort level might be expected to be reduced by one Beaufort number for every 20° C reduction in temperature.

### RELATIONSHIP BETWEEN BEAUFORT NUMBER AND WIND SPEED

Reference height at 33 ft. (10 m)

<table>
<thead>
<tr>
<th>Beaufort Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean m/sec</td>
<td>0</td>
<td>.9</td>
<td>2.4</td>
<td>4.4</td>
<td>6.7</td>
<td>9.3</td>
<td>12.4</td>
<td>15.5</td>
<td>18.9</td>
</tr>
<tr>
<td>Wind speed in Range mph</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>21</td>
<td>28</td>
<td>35</td>
<td>42</td>
</tr>
</tbody>
</table>

**TABLE 1. TENTATIVE COMFORT CRITERIA FOR WINDINESS**

(from Davenport, 1972)
TABLE 2.

Ratio between average air speeds and background flow at points situated in the middle of the space formed by two structures and on the lee-side of the downstream structure, as indicated in Figure 10.

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>RUN 24</th>
<th>RUN 26</th>
<th>RUN 27</th>
<th>RUN 28</th>
<th>RUN 29</th>
<th>RUN 30</th>
<th>RUN 31</th>
<th>RUN 32</th>
<th>RUN 34</th>
<th>RUN 35</th>
<th>RUN 36</th>
<th>RUN 37</th>
<th>RUN 38</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h/4)</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
<td>a b</td>
</tr>
<tr>
<td>0.2</td>
<td>1.6</td>
<td>0.3</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>1.0</td>
<td>1.2</td>
<td>0.3</td>
<td>1.4</td>
<td>-</td>
<td>1.6</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>0.5</td>
<td>-</td>
<td>0.2</td>
<td>0.1</td>
<td>0.0</td>
<td>-</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>-</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.8</td>
<td>-</td>
<td>0.4</td>
<td>0.2</td>
<td>0.0</td>
<td>-</td>
<td>0.0</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>-</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>0.3</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.5</td>
<td>0.4</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td>0.4</td>
<td>0.6</td>
<td>0.7</td>
</tr>
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<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>2.5</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Note: The negative air speeds (-) are very close to zero.
Table 3
Concentrations of gases measured within the spaces formed by rows of nonporous structures and on the lee side of the downstream structure, as indicated in Figure 41

<table>
<thead>
<tr>
<th>Sampling station number</th>
<th>Concentration (ppm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run C-6</td>
<td>Run C-7</td>
<td>Run C-8</td>
</tr>
<tr>
<td>SS-1</td>
<td>2,119</td>
<td>1,449</td>
<td>425</td>
</tr>
<tr>
<td>SS-2</td>
<td>1,702</td>
<td>1,126</td>
<td>1,060</td>
</tr>
<tr>
<td>SS-3</td>
<td>905</td>
<td>617</td>
<td>641</td>
</tr>
<tr>
<td>SS-4</td>
<td>2,059</td>
<td>377</td>
<td>461</td>
</tr>
</tbody>
</table>

ppm = parts per million

Table 4
Concentrations of gases measured within the space formed by parallel structures, on the windwards side and on the lee side of the downstream structure, as indicated in Figure 42

<table>
<thead>
<tr>
<th>Sampling station number</th>
<th>Concentration (ppm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run C-9</td>
<td>Run C-10</td>
<td>Run C-11</td>
<td>Run C-12</td>
</tr>
<tr>
<td>SS-1</td>
<td>479</td>
<td>509</td>
<td>540</td>
<td>587</td>
</tr>
<tr>
<td>SS-2</td>
<td>389</td>
<td>461</td>
<td>581</td>
<td>940</td>
</tr>
<tr>
<td>SS-3</td>
<td>1,461</td>
<td>1,054</td>
<td>491</td>
<td>323</td>
</tr>
<tr>
<td>SS-4</td>
<td>311</td>
<td>275</td>
<td>198</td>
<td>234</td>
</tr>
<tr>
<td>SS-5</td>
<td>216</td>
<td>180</td>
<td>130</td>
<td>67</td>
</tr>
<tr>
<td>SS-6</td>
<td>196</td>
<td>162</td>
<td>105</td>
<td>63</td>
</tr>
</tbody>
</table>

ppm = parts per million
Table 5
Concentration of gases measured within the spaces formed by rows of porous and nonporous structures and on the lee side of the downstream structures, as indicated in Figure 43.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Structure No.</th>
<th>Porosity</th>
<th>Line Sources Connected</th>
<th>Sampling Stations</th>
<th>Concentrations (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>00</td>
<td>1-2-3-4</td>
<td>S-1</td>
<td>1,619</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30%</td>
<td></td>
<td>S-2</td>
<td>1,167</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30%</td>
<td></td>
<td>S-3</td>
<td>1,250</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30%</td>
<td></td>
<td>S-4</td>
<td>1,000</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>30%</td>
<td>1-2-3-4</td>
<td>S-1</td>
<td>1,012</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30%</td>
<td></td>
<td>S-2</td>
<td>1,048</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30%</td>
<td></td>
<td>S-3</td>
<td>1,238</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30%</td>
<td></td>
<td>S-4</td>
<td>1,107</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>30%</td>
<td>1</td>
<td>S-1</td>
<td>1,036</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30%</td>
<td></td>
<td>S-2</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30%</td>
<td></td>
<td>S-3</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30%</td>
<td></td>
<td>S-4</td>
<td>54</td>
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<tr>
<td>4</td>
<td>1</td>
<td>00</td>
<td>1</td>
<td>S-1</td>
<td>1,345</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30%</td>
<td></td>
<td>S-2</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30%</td>
<td></td>
<td>S-3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30%</td>
<td></td>
<td>S-4</td>
<td>46</td>
</tr>
</tbody>
</table>

ppm = parts per million
TABLE 6.
Relative speeds of the outflow air, given as the ratio between the average speeds (measured at
points situated in front of openings on the lee-side wall of porous structures) and the
maximum speed measured in the background flow (outside the boundary layer), for different
space between structures.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Porosities (rows) - %</th>
<th>Distance between Structures (L/H)</th>
<th>Elevations (h/H)</th>
<th>Relative Speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st 2nd 3rd 4th 5th 6th</td>
<td></td>
<td>1st 2nd 3rd 4th 5th 6th</td>
<td></td>
</tr>
<tr>
<td>01</td>
<td>30 30 30 30 30</td>
<td>1.0</td>
<td>0.2 0.44 0.15 0.12 0.08 0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 0.44 0.15 0.12 0.08 0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8 0.46 0.15 0.12 0.08 0.08</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>30 30 30 30 30</td>
<td>1.5</td>
<td>0.2 0.45 0.20 0.22 0.26 0.12</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td>0.5 0.45 0.20 0.22 0.20 0.12</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8 0.46 0.20 0.22 0.20 0.12</td>
<td></td>
</tr>
<tr>
<td>07</td>
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<td>2.0</td>
<td>0.2 0.45 0.22 0.15 0.33 0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 0.45 0.22 0.15 0.33 0.35</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
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</tr>
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<td>0.2 0.46 0.26 0.20 0.30 0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 0.46 0.26 0.18 0.30 0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8 0.46 0.26 0.18 0.22 0.08</td>
<td></td>
</tr>
<tr>
<td>10</td>
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<td>3.0</td>
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TABLE 7.

Ratio between average speeds of the outflow air (measured at points situated in front of openings on the lee-side wall of porous structures) and the background speeds with same elevations for different space between structures

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<tr>
<th>Run No.</th>
<th>Porosities (rows)</th>
<th>Distance between Structures (L/H)</th>
<th>Elevations (h/H)</th>
<th>1st</th>
<th>2nd</th>
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Figure 1. Plan View of The Environmental Wind Tunnel
Cullen College of Engineering, University of Houston

Figure 2. Diagrams Defining Terms
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<th>Effect Caused by the Wind</th>
<th>On Land</th>
<th>At Sea</th>
<th>Beaufort No.</th>
<th>Description</th>
<th>Speed (m sec)</th>
<th>Speed (miles/hr)</th>
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<td>Still; smoke rises vertically</td>
<td>Surface mirror-like</td>
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<td>Calm</td>
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<td>0-0.2</td>
<td>0-1</td>
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<td>Smoke drifts but vanes remain still</td>
<td>Only ripples form</td>
<td>1</td>
<td>Light air</td>
<td></td>
<td>0.3-1.5</td>
<td>1-3</td>
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<td>Wind felt on face, leaves rustle, vane moves</td>
<td>Small, short wavelets, distinct but not breaking</td>
<td>2</td>
<td>Light breeze</td>
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<td>1.6-3.3</td>
<td>4-7</td>
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<td>Leaves and small twigs move constantly, streamer or pennant extended</td>
<td>Larger wavelets beginning to break, glassy foam, perhaps scattered white horses</td>
<td>3</td>
<td>Gentle breeze</td>
<td></td>
<td>3.4-5.4</td>
<td>8-12</td>
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<td>Raises dust and loose paper, moves twigs and thin branches</td>
<td>Small waves still but longer, fairly frequent white horses</td>
<td>4</td>
<td>Moderate breeze</td>
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<td>5.5-7.9</td>
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<td>Small trees in leaf begin to sway</td>
<td>Moderate waves, distinctly elongated, many white horses, perhaps isolated spray</td>
<td>5</td>
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<td></td>
<td>8.0-10.7</td>
<td>19.24</td>
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<td>Large branches move, telegraph wires whistle, umbrellas hard to control</td>
<td>Large waves begin with extensive white foam crests breaking; spray probable</td>
<td>6</td>
<td>Strong wind</td>
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<td>10.8-13.8</td>
<td>25-31</td>
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<td>Whole trees move; offers some resistance to walkers</td>
<td>Sea heaves up, lines of white foam begin to be blown downward</td>
<td>7</td>
<td>Stiff wind or moderate gale</td>
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<td>13.9-17.2</td>
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<td>Breaks twigs off trees; impedes progress</td>
<td>Moderately high waves with crests of considerable length; form blown in well-marked streaks; spray blown from crests</td>
<td>8</td>
<td>Stormy wind or fresh gale</td>
<td></td>
<td>17.2-20.7</td>
<td>39-46</td>
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<tr>
<td>Blows off roof tiles and chimney pots</td>
<td>High waves, rolling sea, dense streaks of foam; spray may already reduce visibility</td>
<td>9</td>
<td>Storm or strong gale</td>
<td></td>
<td>20.8-24.4</td>
<td>47-54</td>
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<tr>
<td>Trees uprooted, much structural damage</td>
<td>Heavy rolling sea, white with great foam patches and dense streaks, very high waves with overhanging crests; much spray reduces visibility</td>
<td>10</td>
<td>Heavy storm or whole gale</td>
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<td>24.5-28.4</td>
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<td>Widespread damage (very rare inland)</td>
<td>Extraordinarily high waves, spray impedes visibility</td>
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<td>Hurricane-like storm</td>
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<td>28.5-32.6</td>
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<td>Air full of foam and spray, sea entirely white</td>
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<td>12</td>
<td>Hurricane</td>
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Figure 3. The Beaufort Scale
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<th>Effects</th>
<th>Source</th>
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<td>Calm, no noticeable wind</td>
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<td>2</td>
<td>1.6-3.3</td>
<td>Wind felt on face</td>
<td>*</td>
</tr>
<tr>
<td>3</td>
<td>3.4-5.4</td>
<td>Wind extends light flag Hair is disturbed Clothing flaps</td>
<td>† +</td>
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<tr>
<td>4</td>
<td>5.5-7.9</td>
<td>Raises dust, dry soil and loose paper Hair disarranged</td>
<td>†, *</td>
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<td>5</td>
<td>8.0-10.7</td>
<td>Force of wind felt on body Drifting snow becomes airborne Limit of agreeable wind on land</td>
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<tr>
<td>6</td>
<td>10.8-13.8</td>
<td>Umbrellas used with difficulty Hair blown straight Difficult to walk steadily Wind noise on ears unpleasant Winborne snow above head height (blizzard)</td>
<td>*</td>
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<tr>
<td>7</td>
<td>13.9-17.1</td>
<td>Inconvenience felt when walking</td>
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<td>8</td>
<td>17.2-20.7</td>
<td>Generally impedes progress Great difficulty with balance in gusts</td>
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<td>9</td>
<td>20.8-24.4</td>
<td>People blown over by gusts</td>
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</tbody>
</table>

* Beaufort land scale [2]
† BRS observations.
‡ Chepil [3].
§ Newburgh [4].
¶ Melbourne and Joubert [5].
‡ Shaw [6].

Note. The decimal values of windspeed arise from speeds being expressed in knots in the original tabulations (1 m/sec = 1.94 knots).

Figure 4. Summary of Wind Effects
(from Penwarden, 1973)
Figure 5. Comfort Conditions for Strolling in Full Sun (a) and for Strolling in Shade (b). (from Penwarden, 1973)
Figure 6. The Process of Analysis to Derive Climatic Design Recommendations
Figure 7. Configuration of The Research Area

Figure 8. Combination of Two Models - 00%, 30% Porosities  
(X1 = 1H, 2H, 3H, 4H, 5H and 6H)

Figure 9. Rows of Models - 00%, 30% Porosities  
(X2 = 1H, 2H, 3H, 4H, 5H and 6H)
Figure 10. Air Speed Studies at Points Situated in the Middle of the Space Formed by Two Structures and on the Lee Side of the Downstream Structures
No. 67  
Porosity = 00

No. 68  
Porosity = 10%

No. 69  
Porosity = 30%

No. 70  
Porosity = 30%

Figure 11. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; height = H; length - 1/20H; distance of the probe from the lee-side surface = 4 1/2H).

Wind direction

No. 77  
Porosity = 00%  
Height = H

No. 71  
Porosity = 30%  
Height = H

No. 83  
Porosity = 25%  
Height = 4/3H

Figure 12. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; length = 1/2H; distance of the probe from the lee-side surface = 3 1/2H).

Wind direction
No. 78
Porosity = 00%
Height = H

No. 72
Porosity = 30%
Height = H

No. 84
Porosity = 25%
Height = 4/3H (elevated)

Figure 13. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; length = H; distance of the probe from the lee-side surface = 3H).

Wind direction

No. 80
Porosity = 00%
Height = H

No. 74
Porosity = 30%
Height = H

No. 86
Porosity = 25%
Height = 4/3H (elevated)

Figure 14. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; length = 2H; distance of the probe from the lee-side = 3H).

Wind direction
No. 81
Porosity = 00%
Height = H

No. 75
Porosity = 30%
Height = H

No. 87
Porosity = 25%
Height = 4/3H

Figure 15. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; length = 3H; distance of the probe from the lee-side surface = 3H).
← Wind direction

No. 82
Porosity = 00%
Height = H

No. 76
Porosity = 30%
Height = H

No. 88
Porosity = 25%
Height = 4/3H

Figure 16. Smoke Visualization Studies in the Vicinity of Isolated Structures Completely Immersed in a Turbulent Flow (width = 4H; length = 4H; distance of the probe from the lee-side surface = 3H).
← Wind direction
Figure 17. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$.

Figure 18. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$. 
Figure 19. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = \( \frac{V_{av}}{V_{max}} \).

Figure 20. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = \( \frac{V_{av}}{V_{max}} \).
Figure 21. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = Vav / Vmax.

Figure 22. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = Vav / Vmax.
Figure 23. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$.

Figure 24. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$.
Figure 25. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = \( V_{av} / V_{max} \).

Figure 26. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = \( V_{av} / V_{max} \).
Figure 27. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$.

Figure 28. Air Speed Profiles on the Downstream Region of an Isolated Structure. The shaded area indicates the size of the cavity. Air speed = $V_{av} / V_{max}$. 
Figure 29. Air Speed Profiles on the Downstream Region of an Isolated Structure. The air speeds are given as the ratio between the average speed at each point and the maximum speed (outside the boundary layer).
Figure 30. Smoke Visualization Studies Within the Space Formed by Two Structures (distance between rows = H).
The smoke concentrations within the first space are higher when the first structure is a nonporous (a) than when it is porous (b). In b the smoke goes through the second and third spaces, although in a it diverts sideways and upwards and enters the second space in small amounts. In c the first structure (not shown in the picture) is nonporous, and in d it is of 30% porosity. The flow characteristics within the third space is almost the same. The pattern within the first space changes when the structures are elevated from the ground (e, f, g).

← Wind Direction
Figure 31. Smoke Visualization Studies Within the Space Formed by Two Structures (distance between rows = 2H).

Within the first space the concentrations are higher in a and e than in b and f, although within the third space the flow characteristics are almost the same in c and d. In b and f some ground level smoke accumulations occurs at the center of the first space. This pattern changes by elevating the upwind structure from the ground (g).

← Wind direction
Figure 32. Smoke Visualization Studies Within the Space Formed by Two Structures (distance between rows = 3H).
Within the first space, the smoke concentrations in a and e are higher than in b and f, although the difference is not as great as it was observed in Figures 30 and 31. As in Figure 31, some ground level smoke accumulation occurs at the center of the first space in b and f. This pattern also changes by elevating the upwind structure from the ground (g and h).

[Wind direction]
Figure 33. Smoke Visualization Studies Within the Space Formed by Two Structures (distance between rows = 4H).
Within the first space, the smoke concentration is higher in the lee-side region of the upwind structure in a than in f. In a, b, c and d the flow characteristics are almost the same. Some ground level smoke accumulations in the middle of the space can be observed (g, d, and f). This pattern changes with the use of structures elevated from the ground (g and h).

← Wind direction
Figure 34. Smoke Visualization Studies Within the Space Formed by Two Structures (distance between rows = 5H).

The flow characteristics within the first and second spaces formed by the structures are similar to the characteristics observed in Figure 33. Same ground level smoke accumulation in the middle of the space can be observed (b, d and f). This pattern changes with the use of structures elevated from the ground (g and h).

← Wind direction
Figure 35. Concentration Visualization in the Vicinity of Rows of Parallel Structures and Within the Space that They Form
Figure 36. Concentration Visualization Within the Space Formed by Parallel Structures With the Same Heights
Figure 37. Concentration Visualization Within the Spaces Formed by Parallel Structures With the Same Heights
Figure 38. Concentration Visualization on the Lee Side Region of A Group of Parallel Structures With Different Heights
Figure 39. Concentration Visualization Around a Group of Parallel Structures With Different Heights.
Concentration vs. color: Yellow = low
Light brown = medium
Dark brown = high
← Wind direction
Figure 40. Concentration Visualization Within a Set of Buildings in a Pattern Similar to the Superblocks in Brasilia.
Concentration vs. color: Light brown = low
Yellow = medium
Dark brown = high

← Wind direction
Figure 41. Concentration Studies Within the Spaces Formed by Rows of Nonporous Tall and Short Structures and on the Lee Side Region of the Downstream Structure.
Figure 42. Concentration Studies in the Windwards Region, Within the spaces Formed by Two Structures and on the Lee Side Region of a Group of Nonporous Structures (concentration data in Table 4).
Figure 42 (cont.). Concentration Studies in the Windwards Region, Within the Spaces Formed by Two Structures and on the Lee Side Region of a Group of Nonporous Structures (concentration data in Table 4).
Figure 42 (cont.). Concentration Studies in the Windwards Region, Within the Spaces Formed by Two Structures and on the Lee Side Region of a Group of Nonporous Structures (concentration data in Table 4).
Figure 42 (cont.). Concentration Studies in the Windwards Region, Within the Spaces Formed by Two Structures and on the Lee Side Region of a Group of Nonporous Structures (concentration data in Table 4).
Figure 43. Concentration Studies Within the Space Formed by Rows of Porous and Nonporous Structures and on the Lee Side Region of the Downstream Structure
Figure 44. Characteristics of the Measurements of the Outflow Air Velocities related to Figures 45, 46 and 47.
Figure 45. Effect of porous and nonporous structures on through-ventilation in downwind structures, for speeds measured at elevation = 4/5 H, according to Fig. 44. In (a) all the structures are of 30% porosity. In (b) the first structure is of 00% porosity and the others are of 30%.

Figure 46. Effect of porous and nonporous structures on through-ventilation in downwind structures, for speeds measured at elevation = H/2, according to Fig. 44. In (a) all the structures are of 30% porosity. In (b) the first structure is of 00% porosity and the others are of 30%.

Figure 47. Effect of porous and nonporous structures on through-ventilation in downwind structures, for speeds measured at elevation = H/5, according to Fig. 44. In (a) all the structures are of 30% porosity. In (b) the first structure is of 00% porosity and the others are of 30%.
Through-ventilation in downstream buildings may be maximized if they are located at a distance equal or greater than 6 building heights (H) from the upstream structure.

This distance may be reduced if pilotis are used, as the wind is diverted downwards and passes through the gap at ground level.

This distance may also be reduced in a group of buildings if larger number of spaces are left between upstream rows of buildings, thus creating a high-porosity set of structures.

Figure 48. Desirable Conditions for Adequate Thermal Comfort and Ambient air Quality.
The concentration distribution is higher at ground level and decreases with altitude.

The air that enters the space \( b \) is at low pollutant concentration. The returning flow from \( b \) does not penetrate the space \( a \). Conditions for thermal comfort are poorer in \( a \) than in \( b \).

A porous short structure causes the returning flow to enter the space \( a \). Conditions for thermal comfort are enhanced in \( a \).

Figure 48 (cont.). Desirable Conditions for Adequate Thermal Comfort and Ambient Air Quality.
Polluted air enters the space b as it is diverted downwards. Concentration in b is higher than in a.

Source at higher elevation (e.g., chimney of a factory, exhaust from upstream buildings, etc.). Concentration is higher in the middle of the plume.

Here conditions of air quality will improve, but conditions for thermal comfort will be poorer in a and b (it applies when the upstream structure is not designed for through-ventilation.

Figure 48 (cont.). Desirable Conditions for Adequate Thermal Comfort and Ambient Air Quality.
The outflow average velocity is about the same at any window elevation.  

surface awnings (pivotal window or shading devices)

The outflow average velocity is likely to be higher at higher elevations due to surface awnings.

Figure 48 (cont.). Desirable Conditions for Adequate Thermal Comfort and Ambient Air Quality.
NOMENCLATURE
NOMENCLATURE

$A_{Du}$ - Heat production per square meter of body surface, W/m²

$C$ - Convective heat exchange

d - Horizontal distance from the structure

$E$ - Evaporative heat loss

$H$ - Structure height

$h$ - Source height, m

$K$ - Proportions of metabolic heat dissipated by means other than evaporation

$M$ - Metabolic rate

$Q$ - Emission rate of pollutants (g/sec)

$P_{wa}$ - $H_2O$ vapor pressure of air, mm.Hg

$R$ - Radiative heat exchange

$R_b$ - Thermal resistance of body tissues, $m^2$ degC/W

$R_c$ - Thermal resistance of clothing, $m^2$ degC/W

$S$ - Solar heat input per square meter of body surface, W/m²

$T_{a, ta}$ - Air temperature, deg C

$T_b$ - Body core temperature

$T_g$ - Temperature of 6-inch black globe, deg C

$T_w$ - Temperature of solid surroundings (walls), deg C

$u$ - Wind speed, m/sec

$\bar{u}$ - Mean wind speed, m/sec

$V$ - Air speed, m/sec

$V_{av}$ - Average air speed, m/sec

$V_{background}$ - Average speed of the background flow, m/sec
$V_{\text{max}}$ - Maximum air speed (outside the boundary layer)

$X$ - Ground level pollutant concentration (g/m$^3$)

$x_1$ - Horizontal distance between structures

$x_2$ - Horizontal distance between structures

$y$ - Lateral distance from the plume axis, m

$\sigma_y$ and $\sigma_z$ - Variance of the concentrations about the plume axis $x(m)$, function of distance $x(m)$