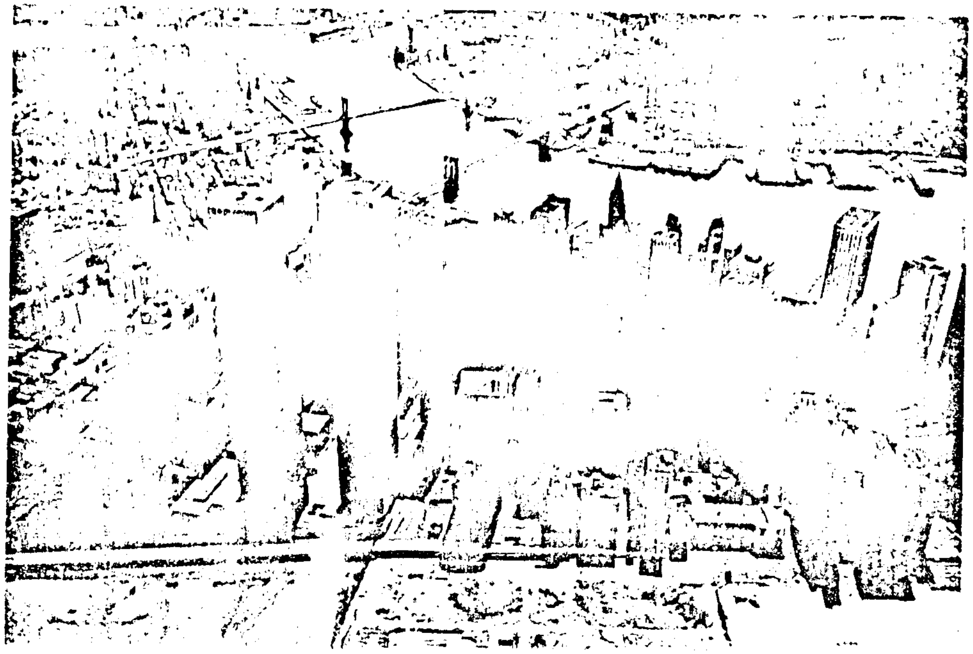
Edward Arens
Department of Architecture
232 Wurster Hall

PREPRINT 81-128

WIND AND BUILDING ENERGY CONSUMPTION: AN OVERVIEW

Edward A. Arens and
Phillip B. Williams

ASCE New York, New York May 11–15, 1981



Cover photo: World Trade Center, New York, New York.

WIND AND BUILDING ENERGY CONSUMPTION: AN OVERVIEW

Edward A. Arens[1] Affiliate member ASCE
Phillip B. Williams[2] Member ASCE

Introduction

The environment around a building affects its energy consumption, primarily by influencing its requirement for space heating and cooling. The environmental variables influencing the amount of energy needed for heating and cooling are outside temperature, humidity, solar radiation, and wind.

Wind influences building energy consumption by affecting the following:

1. Air infiltration and exfiltration from conditioned spaces, resulting from pressure gradients and the resulting mass transfer through building surfaces.

2. The rate of heat transmission to or from external surfaces, partially determined by the turbulent mixing of air close to the building surface.

3. Mechanical systems efficiency. Air circulation around buildings affects the thermal efficiency of air-conditioning cooling towers, and can increase fan power requirements when ventilation inlets and exhausts are poorly located.

4. The necessity for enclosing and conditioning outdoor space. Buildings commonly have uncomfortable surroundings, and architects have responded to this by enclosing the surroundings in atria or malls which need to be heated or cooled. Such enclosure might not be necessary if the site and building were designed to control air movement to an acceptable level.

Air infiltration and exfiltration

Air movement is an important cause of energy loss, particularly in residential buildings, where infiltration commonly causes 30% and up to 75% of the total heat load in winter (1).

Wind affects the air pressure distribution on building surfaces, which controls the heat loss and gain by mass transfer through apertures in the walls and roof. The pressure distribution depends on the following.

(1) The aerodynamics of the building in relation to its surroundings. This determines the velocity/pressure field around the entire building. In isolation, there is an increase in pressure on the windward side of a building and a decrease in zones where flow has accelerated (the corners of the windward side of the

[1] Associate Professor, Department of Architecture, University of California, Berkeley, CA

[2] Principal, Philip Williams Associates, San Francisco, CA

building and the ridge of the roof) or separated (to leeward of the building or of corners). (See Fig. 1.) In the presence of obstructions such as trees or other buildings, the flow and pressure distributions can be considerably more complex.

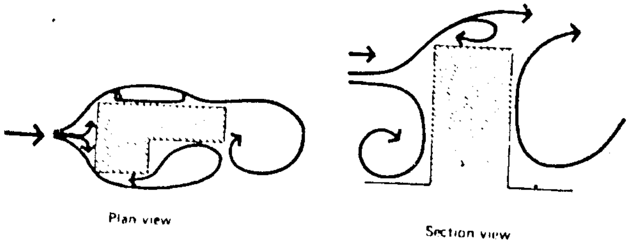


Fig. 1. Sample schematic of air flow around buildings.

(2) The aerodynamic effects of surface features. The geometry of wall and roof architectural features controls the local pressure patterns. This is particularly important around window and door casements, in which the local air pressure next to a crack may be significantly different from the overall pressure on that part of the building (Fig. 2). As a consequence, the rate of air movement in or out of a given portion of wall may depend less on the overall pressure on that portion than on the local pressures directly surrounding the cracks. Simplified wind tunnel tests of a high-rise building surface with protruding mullions show the local surface pressures to vary widely from the overall pressure coefficient of the same surface without mullions (2).

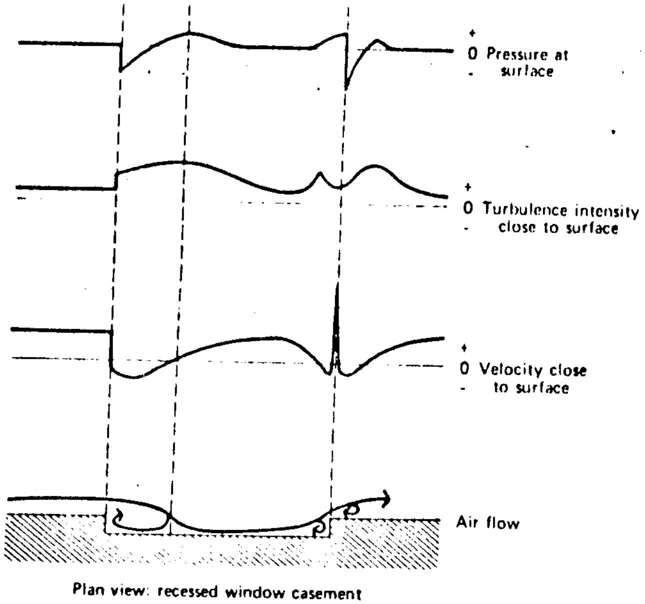


Fig. 2. Characteristics of air flow across a building surface near a recessed window casement.

It should be noted that the pressure distributions at both scales are affected by turbulence in the approaching air flow. This causes the pressure distributions to vary continuously over time. The geometry of the building and its details will also influence local turbulence and the amplitude and frequency of pressure fluctuation.

Heat loss by infiltration is proportional to the amount of flow through the openings in the wall. This is related to pressure and incident velocity as follows:

Microscopic pores: laminar flow, pore diameter < 0.01 in.

$$q \propto \Delta P \propto u^2$$

where q is the volumetric heat flow, P is the pressure difference between interior and exterior, and u is the exterior wind speed.

Cracks and larger openings: orifice flow, crack diameter > 0.01 in.

$$q \propto (\Delta P)^{1/2} \propto u$$

Experimental tracer-gas measurements have shown that air changes in closed unoccupied residences are directly proportional to the average approach velocity. (3,4,5,6) This could be taken to imply that the significant infiltration in houses occurs through crack- or larger-sized openings.

The situation may be complicated by other factors such as human comfort perception. Measurements made in occupied houses in Britain (7) (see Fig. 3) show a large ventilation rate at low speeds due to opened windows. As wind velocity increases, occupants begin to close windows and doors, causing the incremental infiltration rate to decrease. The data suggest that these occupants sensed an acceptable rate of ventilative heat loss and took steps to curtail heat loss above that rate.

In 1974 and 1975, members of the Princeton study group at Twin Rivers, New Jersey, performed wind tunnel and full-scale infiltration tests on a row of two-storey townhouses (1,8).

The tests showed the rate of infiltration was strongly influenced by the direction of the wind approaching the house and by the position of the individual houses in the townhouse row. Infiltration commonly varied by more than 50% between houses of different orientation. Shelter by landscape elements such as trees and fences had similar effects on infiltration rates.

Surface heat transmission

Wind flow around a building causes forced convection heat transfer from and to the walls and roof, resulting in increased energy consumption. The convective heat transfer is caused by the turbulent mixing of air close to the wall due to:

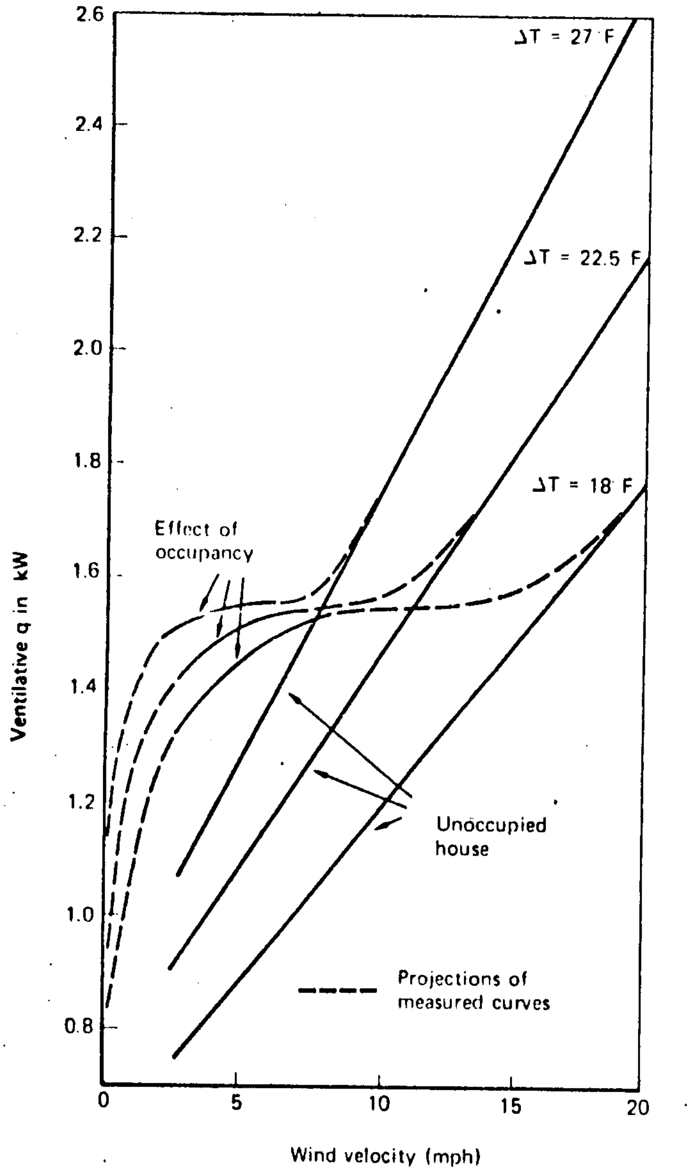


Fig. 3. Ventilative heat loss for a closed and subsequently occupied house of floor area 1000 ft^2. (Source: Dick and Thomas (7).)

(1) the turbulence generated in the wall boundary layer itself,

(2) the wind-flow patterns around the building,

(3) the turbulence inherent in the wind stream.

The method most often used for determining the effect of wind on heat losses takes into account only the first mechanism, that of boundary-layer turbulent mixing. It is based on the "Reynolds analogy", which assumes that, for a turbulent boundary layer in air flows parallel to a plane boundary, the thermal transfer mechanism is the same as the momentum transfer mechanism. The heat losses can then be expressed in the form (9)

$$Nu = \frac{1}{2} Re\, C_f$$

or

$$\frac{h_c x}{k} = \frac{1}{2} \frac{ux}{\nu} C_f$$

where Nu = Nusselt number
Re = Reynolds' number
h_c = convective transfer coefficient
k = conductivity of air
u = wind velocity
ν = kinematic viscosity
x = length from leading edge
C_f = surface drag coefficient

The surface drag coefficient is proportional to velocity: $C_f \propto u^{-1/n}$, where $2 \leq n \leq 5$, depending on the turbulence of the flow. For a given fluid of fixed conductivity and viscosity, therefore, the surface convection coefficient will be proportional to the velocity raised to an exponent between 0.5 and 0.8.

Surface convection is only a part of heat transmission through and from a surface. The overall heat transfer depends as well on radiation from the outside surface, the conductance of the wall, and the interior surface coefficients of radiation and convection.

The total heat transfer q is

$$q = U A \Delta T \tag{1}$$

where A is the area, ΔT is the temperature difference between interior and exterior air, and U, the overall coefficient of transmission, is given by

$$\frac{1}{U} = R_i + R_w + \frac{R_r + R_c}{R_r\, R_c} \tag{2}$$

where R_i, R_w, R_r and R_c (= $1/h_c$) are the resistances of interior surface, wall, exterior surface radiation, and exterior surface convection, respectively.

The external wind affects only the value of R_c. Therefore U varies with wind velocity as shown in Fig. 4. The effect of wind on heat transmission is clearly significant only for poorly insulated materials, such as single-pane glass. A rougher material such as masonry with a higher surface drag coefficient may have twice the convection coefficient of glass but, since the wall resistance of masonry is much greater, the overall variation in surface heat transfer with wind velocity is minimal.

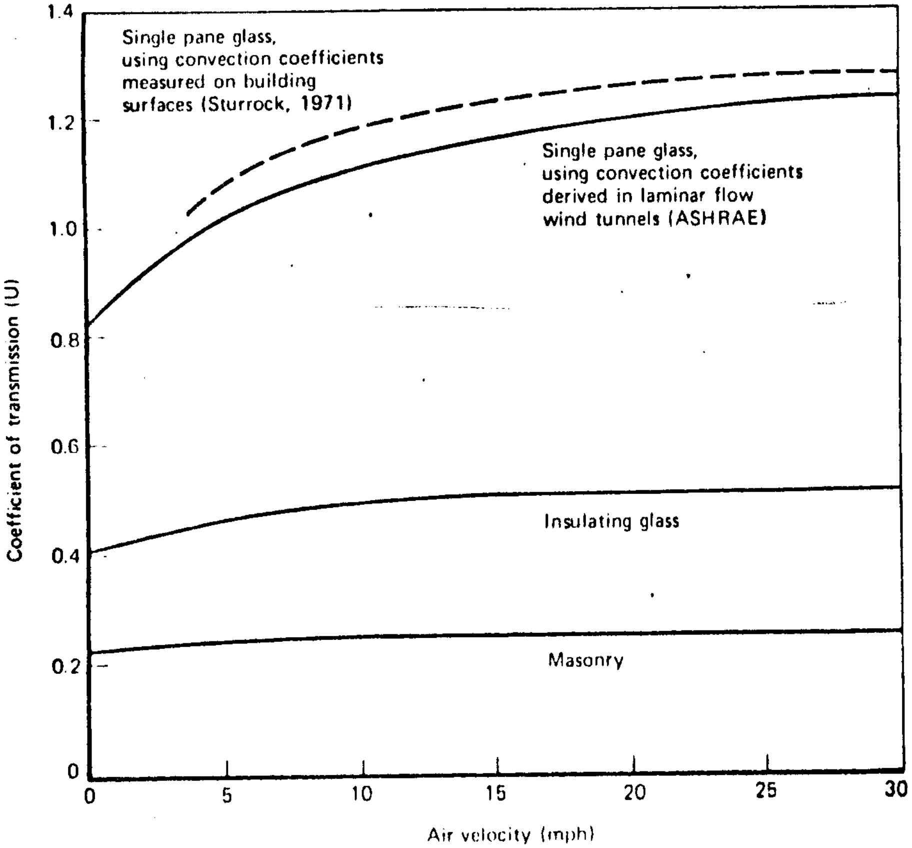


Fig. 4. Effect of air velocity on surface heat transmission.

Use of Fig. 4 will give reasonable approximations for the heat loss from a flat surface at zero incidence (parallel air flow) in a steady air stream with low-intensity isotropic turbulence. Actually, real wind flows around building surfaces are considerably more complex.

The shape of the building and its orientation to the wind strongly influence the wind velocities and flow characteristics in its vicinity. The windflow pattern along each wall will be different (see Fig. 1). On windward faces the flow will accelerate toward the corners; on the leeward side the flow pattern will be determined by the separation eddy. For these conditions, with strong pressure gradients and separated flows, the Reynolds analogy does not apply. On the windward face, the impinging flow causes more heat transfer (10); on the lee side mean velocities will be lower and it would be expected that there would be less heat transfer. However, at certain locations on the lee side, such as flow re-attachment areas, turbulent fluctuations can be very large. Instantaneous high turbulent fluctuations close to the wall surface (even when there is a very small mean velocity) may produce mixing that will exceed the flat plate steady flow case.

In addition to the overall aerodynamics of the building, small-scale architectural features affect the airflow. Protrusions from the surface, such as mullions and window frames, increase turbulent mixing and hence heat loss (see Fig. 2).

The nature of the approaching wind flow itself will affect the flow pattern around a building. Buildings are situated in the earth's boundary layer, whose wind velocity and turbulent intensity distribution vary according to the upwind topography (see Fig. 5).

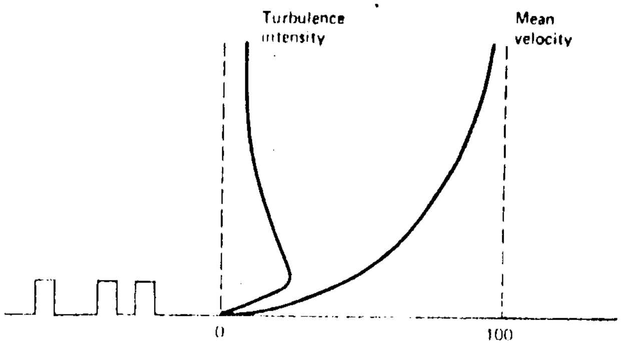


Fig. 5. Velocity and turbulence intensity profiles in the atmosphere, scaled to the gradient wind velocity at the top of the boundary layer. (Source: Counihan (11).)

The high turbulent intensities of the atmospheric boundary layer will be superimposed on the turbulent structure of the wall boundary layer and will increase the amount of turbulent mixing and hence heat transfer at the wall surface.

It would appear that, because of the wind-flow effects around the building and the nature of the wind itself, the convective heat losses from an actual building would be higher than that predicted by using the Reynolds analogy for parallel flow on a flat plate. Unfortunately, little work has been done to examine the heat loss relationships for actual building shapes immersed in the earth's boundary layer. Sturrock's measurements (10) of convective losses for simple building shapes in the wind tunnel are approximately 50% higher than those given by the parallel flow flat-plate formula. A surface forced convection coefficient 50% higher for single-pane glass would result in the U-values shown by the broken line in Fig. 4.

It can be seen that the variation in overall surface heat transmission between high velocities (30 mile/h) and very low velocities 3 mile/h) is of the order of 30% for single-pane glass. A typical office block in a zone where single glazing is common, such as San Francisco, loses approximately 20% of its heat through surface heat transmission. Thus, one might expect the wind to cause 10% of the total heat transfer to the environment. Practically, however, the designer cannot reduce the wind speed or turbulence by more than perhaps 60%. The resulting reduction of the building's total heat load becomes very small, on the order of 3%.

Mechanical systems efficiency

Wind controls the circulation around structures, influencing the location and effectiveness of ventilation inlets and exhausts and/or air-conditioning cooling towers. Failure of cooling tower systems to perform to specifications during wind is a common problem.

Wind influences the energy requirements of mechanical systems in two major ways:

> it can cause inadvertent exhaust recycling, reducing thermal efficiency of cooling equipment and heat pumps;
>
> the pressure gradients it induces affect the fan power requirements for exhausts, inlets and cooling towers.

Attempts to avoid these problems have led designers to space exhausts and inlets far apart, increasing ductwork and fan power requirements. Knowledge of wind influences might be used to advantage to allow designers to minimize the distance between inlets and exhausts, thereby reducing the load on fans and the amount of materials invested in ductwork, and increasing the feasibility of waste energy retrieval equipment.

There does not appear to be published literature on the magnitude of wind-induced mechanical inefficiencies, although these can be serious. In San Francisco there are examples of cooling towers on high-rise buildings that lose 70% of their cooling capacity during the daily 20-30 mile/h sea breeze.

Chapter 14 of the forthcoming 1981 ASHRAE Handbook of Fundamentals contains an extensive discussion of air flows around buildings and its effect on mechanical systems (12).

Necessity for enclosure; climate of the building's environment

The spaces around buildings may be used for human activities if their climates are comfortable for people engaged in those activities. Because many shopping plazas, passageways and building entrances have been found to be uncomfortable due to excessive windiness or poorly-controlled climate, architects have been tending to enclose them as indoor lobbies and malls, either remedially or as part of the initial design (13). Appropriate climatic design of such outdoor spaces and their surrounding buildings could in some cases obviate the need for these enclosures, thus saving the energy costs of materials, construction, heating, air conditioning, lighting and maintenance of indoor spaces.

Successful design of outdoor spaces depends on knowledge of the local climate that will exist in a planned outdoor space, and on knowledge of whether that climate will be comfortable for people engaged in the activities that are planned for that space (i.e., seated activities require warmer and more controlled climates than pedestrian activities, where people generate more metabolic heat and are free to move to maintain their comfort).

Considerable interest is developing in the study of civilian comfort in urban outdoor surroundings. Research on the effect of wind on comfort in cold climates (14,15,16,17) is fairly advanced and begins to explore the design implications of the comfort criteria it has established. Wind is generally undesirable in cool conditions because it increases the rate of heat loss from the body through windchill. Conversely, wind has a beneficial effect on comfort in hot climates, where increased ventilation aids evaporative heat loss (18).

In the climatic design of unenclosed spaces, the factors to be adjusted are the following:

> Hot climates: promote wind ventilation; block sun from the inhabitated areas; use surfaces with high thermal admittance.
>
> Cold climates: block wind; expose the inhabited spaces to sun.

Outdoor design accommodating both hot and cold seasons is very possible and there are many examples of this in the world's traditional architecture.

It is also possible to enclose spaces without heating or cooling them. The Galleria in Milan and Wright's Marin Civic Center are examples of large common malls that admit sunlight through glass roofs and are cooled through natural ventilation by thermal and wind-induced convection.

COMBINED EFFECT OF WIND ON VARIOUS TYPES OF BUILDINGS

The total effect of wind on heat transfer tends to depend on the type of building. The relative importance of the four types of wind effects described above are presented below by major building type.

Office buildings

(1) Infiltration is often negligible on large office buildings with sealed windows; it is controlled more by the operation of the mechanical ventilation system than by the exterior wind.

(2) The fraction of total energy cost attributable to aerodynamic influences on surface transmission will approach 10% in large-scale office buildings of conventional design. This depends primarily on the area of glass, and also on the surface-to-volume ration of the building. The designer is unlikely to be able to influence more than a few percent of the building's total energy consumption by applying wind-control devices to the facade.

(3) Mechanical systems dominate the energy requirements of office buildings. Wind-induced inefficiencies might be of the order of 5% of total energy requirements on an annual basis; there is room for research on this and on ways of designing wind-efficient inlet and exhaust systems.

(4) Office towers commonly produce very windy surroundings, and architects have recently been responding to this by enclosing the exterior space around them in atria or malls.

Residential low-rise

(1) Infiltration studies on residences have been described above. Townhouse units with openable windows commonly lose more than 30% of their total winter heating load to infiltration, which is highly responsive to wind action (Fig. 3).

(2) Approximately one-third of the total winter heat loss from residences is via surface transmission from walls and roof, and another one-third from windows. The effect of wind on wall and roof surface transmission is negligible, but wind can double the heat transmitted through single-pane windows.

(3) Wind effect on the efficiency of mechanical systems is generally unimportant in residential-scale buildings.

(4) Effective landscaping and house design could, in many cases, make outdoor spaces more livable and eliminate the need to enclose and heat them. Similarly, houses in hot climates designed to use the wind for natural ventilation save the substantial energy needed for air conditioning.

Residential high-rise

(1) Infiltration and exfiltration due to wind cause the primary heat loss from residential high-rise units with openable windows and doors to balconies. Fig. 6 is a schematic diagram of the pressure distribution on the face of a high-rise apartment block with balconies; the inset shows the flow pattern around the entire building. It can be seen that the positive and negative local pressures at the top and bottom of the balcony space exceed the total pressure, and that this can cause substantial air leakage through the joints of sliding doors and windows.

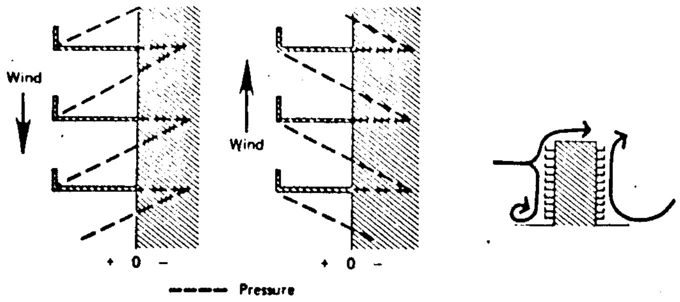


Fig. 6. Pressure distribution on the face of a building with balconies.

(2) Surface transmission heat losses from residential high-rises should be the same as for office buildings, except that the areas of glass are generally less.

(3) Mechanical systems efficiency is probably affected by wind to a degree similar to that for office buildings.

(4) The issue of whether outdoor spaces should be enclosed generally does not apply to this type of construction.

Commercial

(1) Infiltration, (2) surface transmission, (3) mechanical systems--with the many different types of commercial buildings, these factors are too variable to discuss specifically. (4) the questions of whether to enclose a space and whether to control its climate depend partly on wind. The tendency toward enclosure in shopping center design has important energy implications. Examples of malls that had to be enclosed because of unacceptable wind conditions are given by Penwarden and Wise (13).

CONCLUSION

Some information has been presented on how wind affects building heating and cooling, and the relative importance of these effects for different types of buildings.

Existing research is sparse and there is much room for research on wind effects. Particular examples are:

-infiltration on houses versus siting and landscaping;

-infiltration on high-rise residential blocks,

-wind effect on the mechanical systems of tall buildings;

-better climatic design of outdoor spaces and indoor spaces without energy-consuming climate control.

REFERENCES

1. Mattingly, G.E. and Peters, E.F., "Wind and Trees-Air Infiltration Effects on Energy in Housing," Princeton University, Center for Environmental Studies, Rep. No. 20, 1975. (Also published in J. Ind. Aerodynamics, 2(1) (1977).)

2. Leutheusser, H.J., "Influence of Architectural Features on the Static Wind Loading of Buildings," National Bureau of Standards, Building Science Series 30: Wind Loads on Buildings and Structures, R.D. Marshall (ed.). Government Printing Office, Washington, D.C., 1970.

3. Dick, J.B., "Experimental Studies in Natural Ventilation of Houses," *J. Inst. Heating Ventilating Eng.*, 17 (1949) 420-466.

4. Dick, J.B., "The Fundamentals of Natural Ventilation in Houses," *J. Inst. Heating Ventilating Eng.*, 18 (1950) 123-134.

5. Ross, H., and Grimsrud, D., "Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda," DOE report LBL-W7822, 1978.

6. Sherman, M., and Grimsrud, D., "Infiltration-Pressurization Correlation= Simplified Physical Modeling", *ASHRAE Transactions* Vol. 86: 1980, pp. 778-807.

7. Dick, J.B. and Thomas, D.A., "Ventilation Research in Occupied Houses," *J. Inst. Heating Ventilating Eng.*,19 (1951) 306-326.

8. Harrje, D., Heisler, G., and Buckley, C., "Building Energy Reduction= Optimum Use of Windbreaks., Preprint, ASCE International Convention, New York, May 11-15, 1981.

9. Schlichting, H., *Boundary Layer Theory*, McGraw-Hill, New York, 1968.

10. Sturrock, N.S., "Localized Boundary Layer Heat Transfer from External Building Surfaces," *Ph.D. Thesis*, University of Liverpool, 1971.

11. Counihan, J. "Simulation of an Adiabatic Urban Boundary Layer in a Wind Tunnel," *Atm. Environ.*, 7, (1973) 673-689.

12. *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, New York.

13. Penwarden,A.D. and Wise, A.F.E., "Wind Environment Around Buildings," *Building Research Establishment Report*, Her Majesty's Stationery Office, London, 1975.

14. Hunt, J.C.R., Poulton, E.C. and Mumford, J.C., "The Effects of Wind on People; New Criteria Based on Wind Tunnel Experiments," *Building Sci.*, 1975.

15. Lawson, T.V. and Pen, A.D., "The Effects of Wind On People in the Vicinity of Buildings," *Proc. 4th Int. Conf. on Wind Effects on Buildings and Structures*, Cambridge University Press, London, Sept. 8-12, 1975.

16. Melbourne, W.H., "Criteria for Environmental Wind Conditions," *Journal of Industrial Aerodynamics*, vol. 3, 1978, pp. 241-249.

17. Arens, E., "Designing for An Acceptable Wind Environment," *Journal of the Transportation Engineering Division*, ASCE, Vol. 107, No. TE2, Proc. Paper 16132, March 1981, pp. 127-141.

18. Arens, E., Berglund, L., Gonzales, R., McNall, P., Zeren, L., "A News Bioclimatic Chart for Passive Solar Design," *Proceedings of the Fifth National Passive Solar Conference*, Amherst, Mass., October 1980, pp. 1202-1206.