Journal of Wind Engineering and Industrial Aerodynamics, 10 (1982) 287—301 287
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

#1113

DISTRIBUTION OF WIND- AND TEMPERATURE-INDUCED PRESSURE DIFFERENCES ACROSS THE WALLS OF A TWENTY-STOREY COMPARTMENTALISED BUILDING

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(Received November 1, 1981; accepted in revised form March 1, 1982)

Summary

An experimental investigation has been made of the distribution of pressure differences across the walls of a 20-storey student residence building at the University of Ottawa. The wind velocity at the test building as well as the temperature distributions both inside and outside the building were measured simultaneously.

While pressure differences are caused by all three of the factors investigated, namely the temperature gradient (stack effect), the wind and the mechanical ventilation system installed in the building, the first two effects are predominant for this particular building during the winter season.

The stack effect is found to be linearly proportional to the difference of the reciprocal outside and inside (absolute) temperatures, and varies almost linearly with height. The neutral pressure level occurs at a height of ~40 m, or 70% of the height of the building.

The wind-induced pressure difference under relatively strong wind shows a good conformity with previous knowledge for typical bluff sections such as a rectangular prism.

Notation

C, C_1, C_2	coefficients
g	acceleration due to gravity
M	molecular weight
ΔP	pressure difference
R	universal gas constant
T	temperature
V	mean velocity of wind
z	elevation above ground
α	power-law exponent
θ	wind direction, taken clockwise from $\theta = 0°$ (true north)

Subscripts

i	inside
o	outside
r	reference
s	stack
v	ventilation
w	wind

Introduction

Rapidly rising energy costs together with increased concern over the depletion of energy resources have caused growing interest in energy thrift. The thermal performance of the building enclosure both in residential and public buildings has accordingly received greater attention recently.

In the design of buildings, however, prediction of the energy requirements due to air infiltration through the building skin is not without difficulties. For example, Shaw [1] reported a considerable discrepancy between the measured air-leakage characteristics of multi-storey apartment buildings and those calculated in accordance with the recommendations of ASHRAE [2]. Air infiltration under wind action is also an important problem which has not been fully clarified.

Estimating the quantity of air infiltration requires knowledge of the pressure difference across the building exterior under various meteorological and occupancy conditions, as well as the air-leakage characteristics of each wall and window pane, etc. [3]. The objective of the present study is to establish, by measurements on a high-rise building, the pressure differences induced by the temperature gradient, the wind and the mechanical ventilation system installed in the building.

Experimental

Test building

The measurement of pressure differences was carried out on a 20-storey student residence building at the University of Ottawa. The building is ~56 m high and 22 m × 27 m in plan, having in addition a penthouse 7 m high. The west side of the building is partly shielded by an adjacent six-storey building and faces the built-up city centre area ~1 km ahead. The other three directions are exposed to relatively open terrains, with lower buildings of up to four storeys. The general layout of the building and the surrounding area is shown in Fig. 1.

The exterior walls of the building comprise a 200 mm thickness of concrete, 50 mm of insulation with a vapour barrier, and 10 mm of dry wall. All the windows are of the openable double-glazed aluminum sliding type, except for those on the lowest two floors.

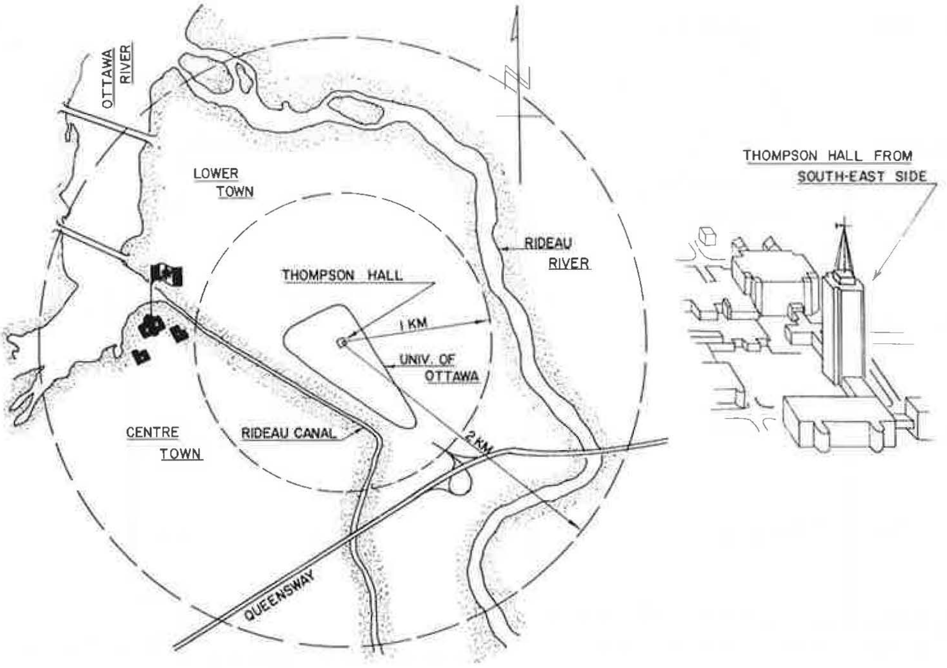


Fig. 1. Location of test building.

The main air-handling system is located in the penthouse. The rated capacities of the major supply and exhaust fans are 18.6 $m^3\ s^{-1}$ and 8.2 $m^3\ s^{-1}$, respectively, at a pressure of 500 Pa. There are two more small supply systems on the first and second floors.

Pressure measurements

Pressure differences across the exterior walls were measured at four different levels: the 3rd, 8th, 13th and 18th floors. The corresponding elevations are shown in Fig. 2 together with the locations of pressure taps and transducers on a typical floor plan. The tip of each pressure tube, made of stainless steel (6.4 mm o.d.), was supported through an angle-bracket attached to the outside wall to ensure that the tip was normal to the building wall. Two or three pressure tubes facing the same direction at the same level were connected in parallel through 6.4 mm plastic tubing to give a pneumatically averaged value of the external pressure on each side at each level, as shown in Fig. 2. MKS Baratron-type differential pressure transducers were used for the measurements, taking the difference between the internal and external pressures, at each location. A total of 44 pressure taps were thus connected to 16 transducers.

Temperature measurements

Two thermocouples were installed at each level to measure both the

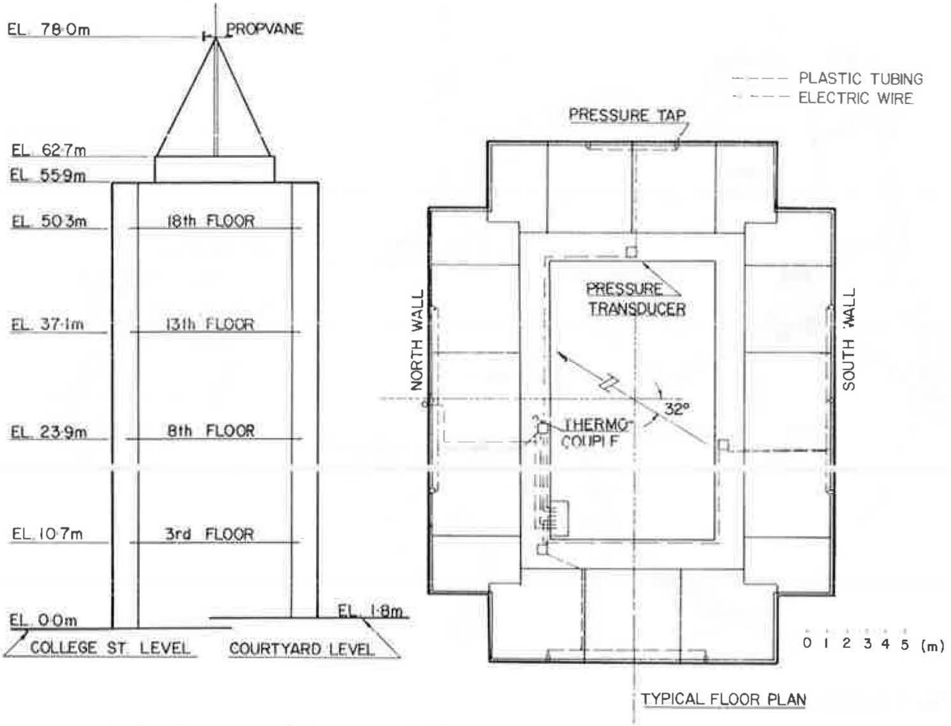


Fig. 2. Building layout and instrumentation.

internal and external ambient temperatures at a total of four levels on the north side of the building. One extra thermocouple was mounted ~10 m above the roof on a radio tower on top of the penthouse. All of the thermocouples used were K-type (chromel—alumel), sheathed in 250 mm long, 1.0 mm stainless-steel tubing and ungrounded. Each of them was connected to the data-processing system through its own electric ice point, an Omega-type MCJ-K.

Wind measurements

Simultaneous measurements of both wind speed and direction were carried out by means of a Gill Propvane together with an RWSU Blue Box [4], developed by the Low Speed Aerodynamics Laboratory of the National Aeronautical Establishment (NAE), National Research Council of Canada. The installation of the Propvane with a 22 m tower on top of the penthouse was carried out by NAE, and access to the data was given to the authors.

Data acquisition

The measured data, in the form of DC voltages from 16 pressure transducers, nine thermocouples and the Propvane, were acquired at a rate up to 105 cycles per hour using an HP3052A data-acquisition system and were processed by an HP9835 computer.

The measurements were made continuously for 5 months from November 1980 to March 1981, and hourly averaged data for all 27 channels were stored on magnetic tape.

Analysis of results

A difference between the internal and external pressures on a building can be caused by various factors. Three sources are considered here, namely:

(i) wind-induced external and internal pressures;

(ii) natural ventilation caused by temperature differences, the so-called stack effect; and

(iii) forced or mechanical ventilation systems.

The analysis of the data measured in this study is carried out on the assumption that the total pressure difference Δp is given by linear summation of these three kinds of pressure differences, i.e.,

$$\Delta p = (\Delta p)_w + (\Delta p)_s + (\Delta p)_v \tag{1}$$

where Δp is the total pressure difference across the wall, $(\Delta p)_w$ is the pressure difference caused by wind action, $(\Delta p)_s$ is the pressure difference caused by the stack effect, and $(\Delta p)_v$ is the pressure difference caused by mechanical ventilation.

The building was essentially vacant during the Christmas holiday season and the major mechanical ventilation system was shut down throughout this period. The evaluation of the stack and wind effects was, therefore, performed using the data obtained during this period, in which only the first two terms on the right-hand-side of eqn. (1) are included.

Stack effect

When the mechanical ventilation is shut down and wind effects are negligibly small because of low windspeed, the pressure difference will be caused predominantly by the stack effect. Assuming that the variation of temperature with height, both in the atmosphere and inside the building, is small and negligible, the pressure difference in this case can be approximated by the equation

$$(\Delta p)_s = C_1(1/T_o - 1/T_i)(C_2 - z) \tag{2}$$

where $(\Delta p)_s$ is the pressure difference caused by the stack effect at an elevation z (m) above ground, T_o is the outside temperature (K), T_i is the inside temperature (K), and C_1, C_2 are constants: C_2 corresponds to the neutral pressure level (NPL), i.e., the height at which the inside and outside pressures are equal.

Some fifteen or more cases with an hourly wind speed of less than 1.0 m s^{-1} were chosen from the measurements. The results are plotted in Figs. 3 and 4. T_o and T_i in these plots are averages of the outside and inside temperatures measured at each of the four levels.

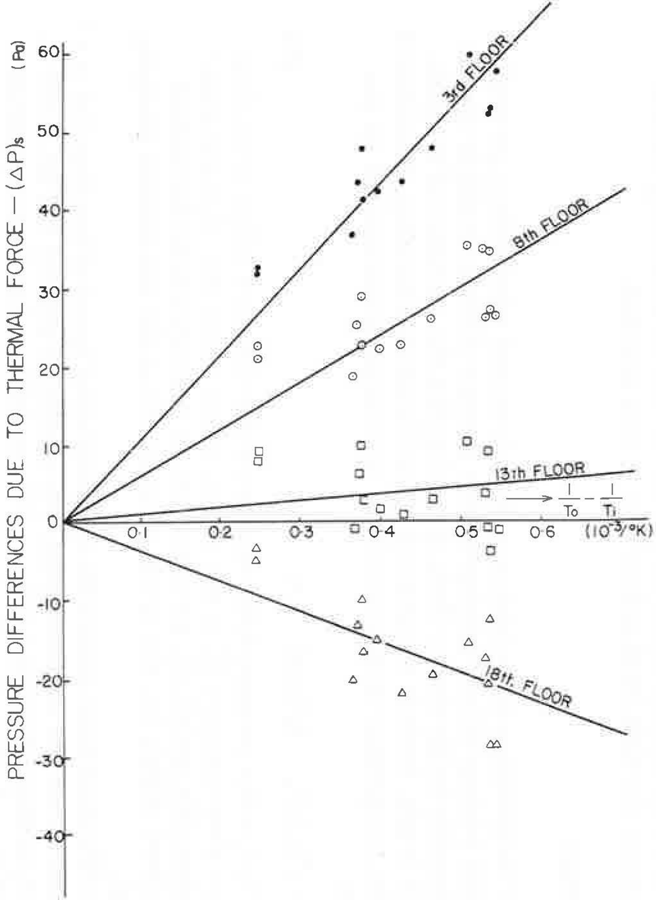


Fig. 3. Pressure difference due to stack effect (observed during period when building was vacant).

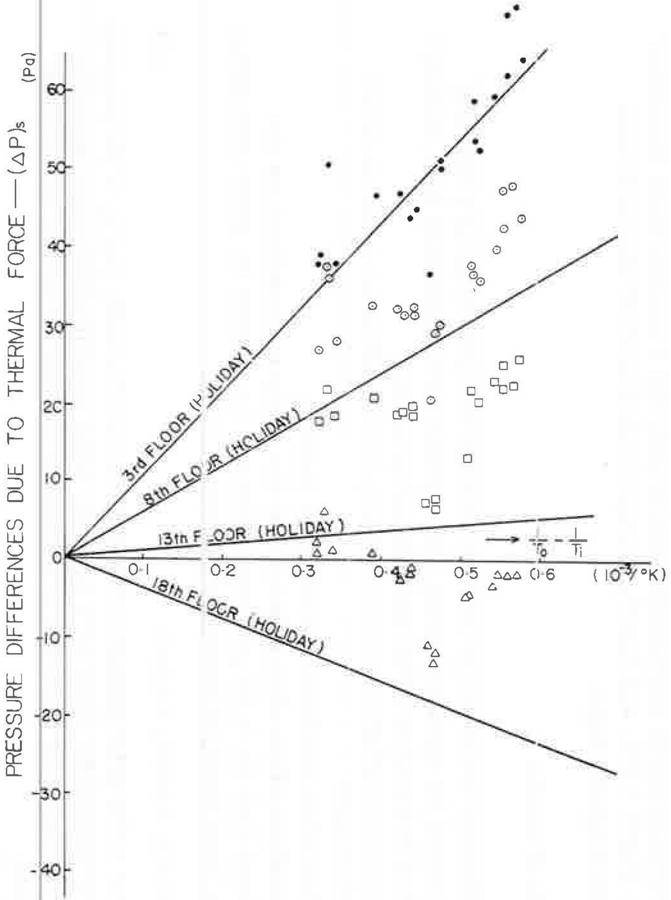


Fig. 4. Pressure difference due to stack effect (observed during period when building was occupied). Regression lines are based on the data during Christmas holidays and given here for comparison only.

Figure 3 depicts $(\Delta p)_s$ during the Christmas holidays at each of the four levels as a function of the difference of the reciprocal temperatures. If eqn. (1) is applicable, the constants C_1 and C_2 can be determined from this figure. The four linear-regression lines in Fig. 3 were obtained using the simple least-squares method. Despite the apparently diverse data distribution, the values of C_1 and C_2 estimated from any two of the regression lines are found to be consistent. The estimated NPL or C_2 is ~40 m, or 70% of the height of the building, which is perhaps a little high when compared with previous measurements on tall buildings [5]. The coefficient C_1 is plotted against temperature change in Fig. 5 to show their linear relationship. C_1 in this figure was obtained from the vertical profile of $(\Delta p)_s$, as shown in Fig. 6. A theoretical estimate of C_1, assuming that the atmospheric pressure is 1 atm. at ground level, may be obtained as

$$C_1 = Mgp_o/R = 3.44 \times 10^3 \text{ Pa K m}^{-1} \tag{3}$$

where $g = 9.81$ m s^{-2} (the acceleration due to gravity), $p_o = 101.3 \times 10^3$ Pa (= 1 atm.), $M = 28.8$ g (the equivalent molecular weight of air), and $R = 8.314$ J K^{-1} (the universal gas constant). This value compares favourably with the measured value, $C_1 = 3.70 \times 10^3$ Pa K m^{-1}.

The effect of natural ventilation was examined when the building was occupied by the residents. Figure 4 shows some of the results compared with the regression lines obtained during the holiday season (Fig. 3). The pressure differences during the time when the building was occupied are found, particularly at the higher levels of the building, to be considerably greater than those for the vacant building. The neutral pressure level (NPL) in this case is found to occur at almost 90% of the total building height, and the coefficient appears to be ~2.75×10^3 Pa K m^{-1}, which is lower than the

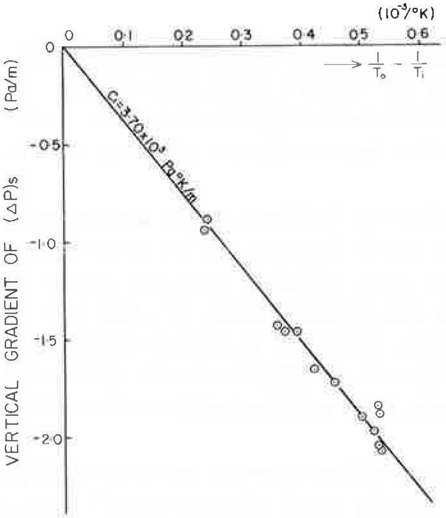
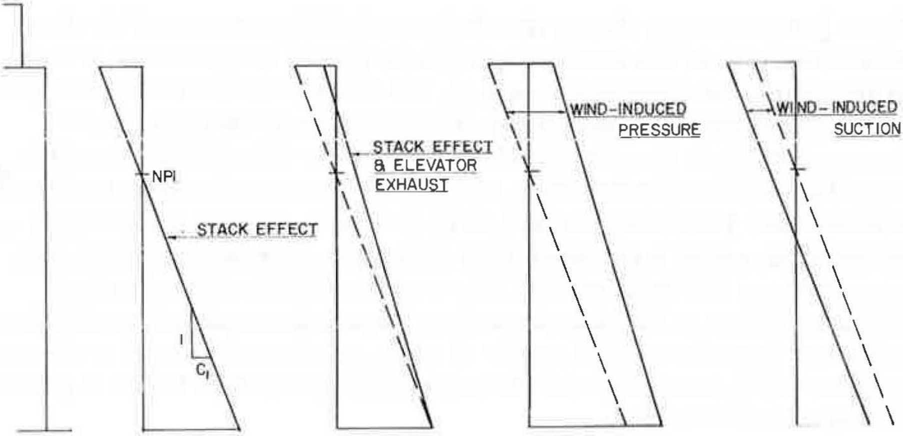


Fig. 5. Vertical gradient of pressure difference due to thermal effect.



(a) No wind, no ventilation. Building "unoccupied"
(b) No wind, elevator exhaust only. Building "occupied"
(c) Stack effect and wind-induced pressure
(d) Stack effect and wind-induced suction

Fig. 6. Various patterns of pressure-difference profile.

value given by eqn. (3). This phenomenon is discussed below in connection with the ventilation system.

The stack effect was found to be one of the major causative factors in the mean pressure difference across the building enclosure throughout the winter season. Its magnitude, in this particular set of measurements at the lower levels of the building, was as high as 70—80 Pa. This is comparable to the wind-induced positive pressure at a local mean wind-speed of ~12 m s^{-1}.

Wind effects

The distribution of wind-induced pressures is affected by various factors, such as the building shape, its dimensions, the surface roughness of the building, the surrounding topography, and meteorological conditions. A description of the general characteristics of the mean external pressure caused by wind can be found elsewhere [6].

From the data obtained during the Christmas holidays, some strong-wind cases were chosen to evaluate the average wind effect on the pressure difference across the building skin. The mechanical ventilation was shut down except for the heating fan for the ground and second floors; this fan was regulated at a temperature lower than usual. From the measured inside and outside temperatures, the effect of natural ventilation can be estimated using the results of Fig. 3. This amount was then subtracted from the measured total pressure difference.

Figure 7 shows the wind-induced pressure differences on the four walls for various wind azimuths. Results are given for the third (elevation 10.7 m) and 18th floors (elevation 50.3 m), and are normalised by the dynamic pressure

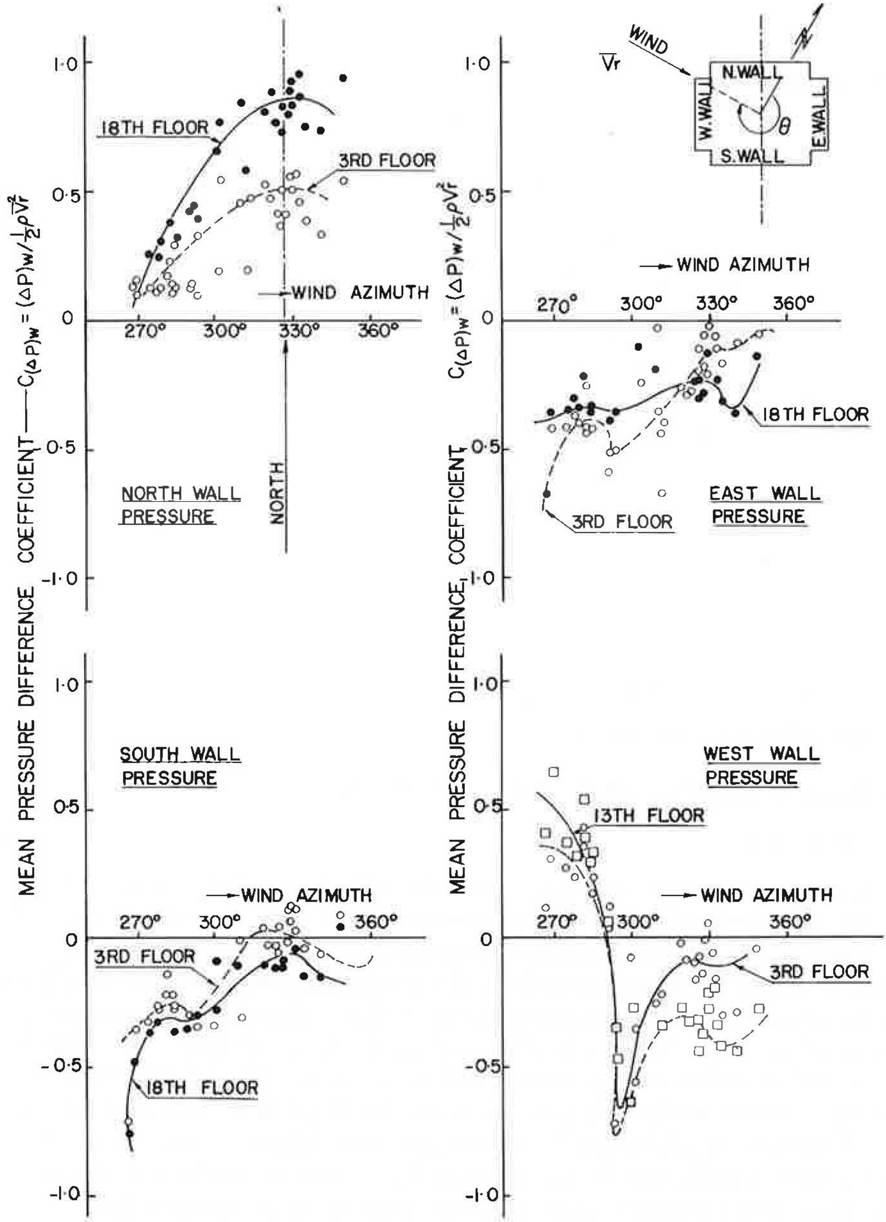


Fig. 7. Wind-induced pressure difference.

$\rho V_r^2/2$ at the reference height (z_r = 78.0 m). A considerable difference in the magnitudes of the pressures between these two levels is observed, as expected.

The height-dependence of pressure is depicted more clearly in Fig. 8, which shows a few cases of the vertical profile of wind-induced pressure measured when the wind was incident nearly perpendicular to the wall. Assuming the

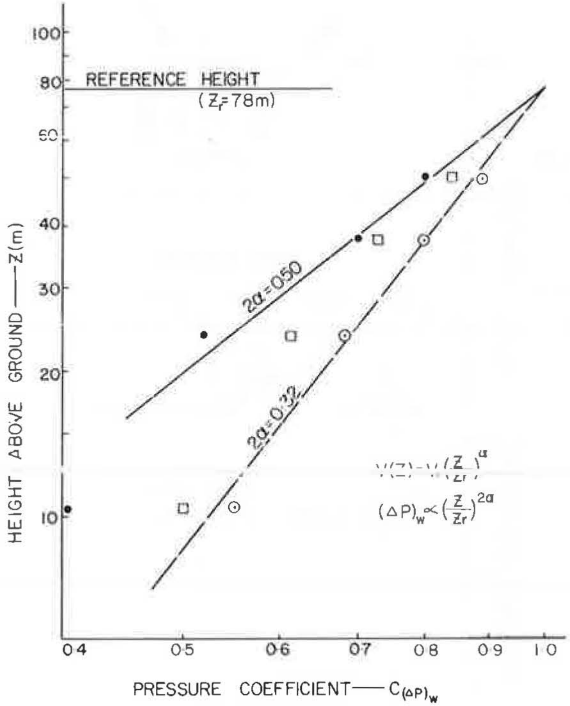


Fig. 8. Wind-induced normal pressure.

conventional power-law profile of the mean wind:

$$V(z) = V_r(z/z_r)^{\alpha} \tag{4}$$

where V_r is the reference speed at the reference height z_r(m), the power-law exponent α corresponding to these pressure profiles is in the range 0.16—0.25. This is comparable to that for standard exposure for suburban areas [7].

Figure 9 shows a typical example of the vertical pressure profiles on all four walls with the wind from building north ($\theta = 328°$). Since the measurements were made during the winter season, the range of wind azimuth was limited to the prevailing northwest quadrant. However, considering the fact that the cross-section of the building is nearly symmetrical (and disregarding the effects of surrounding topography on the pressure patterns), the measurements on all four walls can be approximately combined together as shown in Fig. 10. Here, the pressure is again taken at the reference wall (north). The wind azimuth may be considered to cover almost all directions by taking the relative angle between the actual wind azimuth in each measurement and the direction of the wall on which the data were obtained. For example, the pressure reading on the north wall for a westerly wind ($\theta = 238°$) in this figure is taken to be equivalent to the pressure reading on the south wall for an easterly wind, or the reading on the west wall for a southerly wind, and so on.

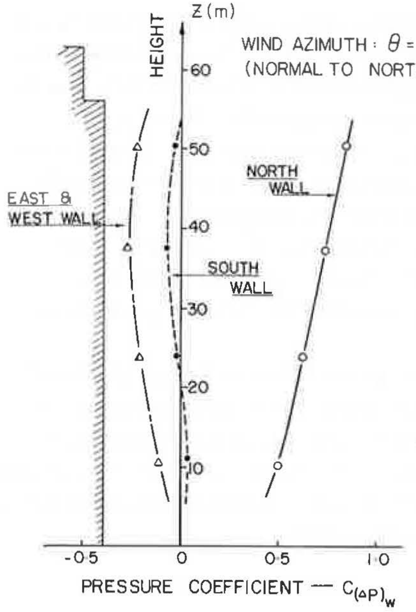


Fig. 9. Typical vertical profile of wind-induced pressure.

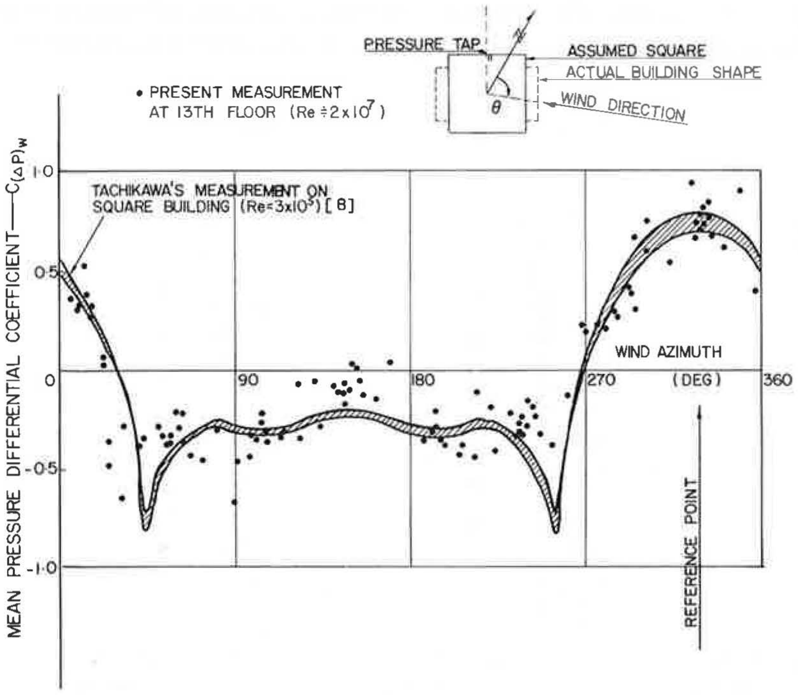


Fig. 10. Deduced wind-induced pressure difference versus wind azimuth.

The measurements plotted in Fig. 10 are those obtained at the 13th floor (elevation 37.7 m), where the pressure pattern is expected to be nearly two-dimensional. This pressure pattern was found to be typical of a nearly square building section. The results show excellent agreement with the measurements of Tachikawa [8], in which the absolute external pressure distribution was measured on a square test building. Comparison with wind-tunnel data for a two-dimensional model of square section shows a generally similar pattern except that the nearly constant base pressure at the leeward side tends to show larger suction when the model is tested in smooth flow at a relatively low Reynolds number [9]. The wind-induced internal pressure is not considered separately here.

As described above, the lower west side of the building is partly shielded by a neighbouring building, whereas the other three directions are exposed to moderately smooth suburban terrains. Since the present measurements were limited to cases produced by seasonal winds from the northwest quadrant, the effects of this difference in upstream fetch and the corresponding difference in wind turbulence characteristics were not noticeable.

Mechanical ventilation

The mechanical ventilation system in the building investigated is generally operated on a fixed schedule. The ventilation-induced pressure difference was deduced from the data obtained in relatively calm hours (with a mean wind

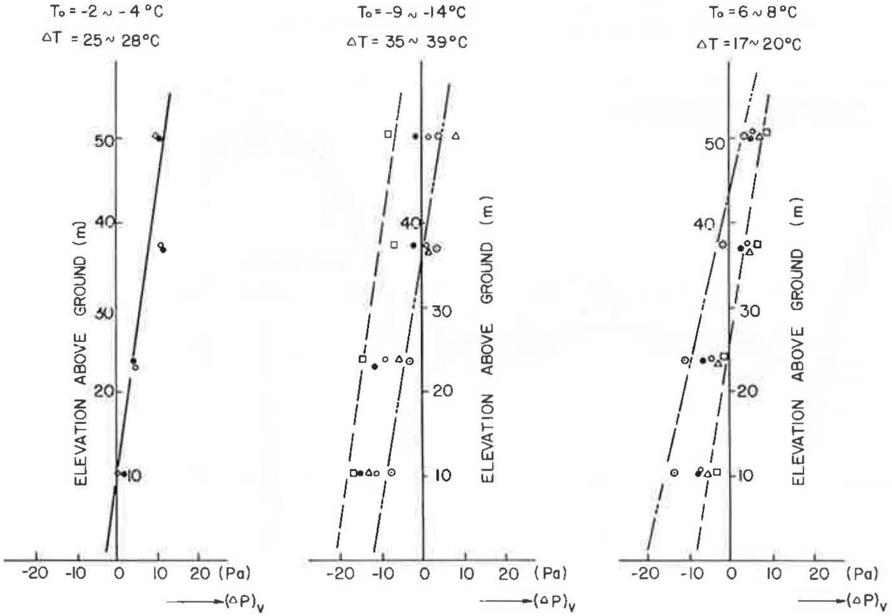


Fig. 11. Pressure difference due to forced ventilation system.

speed less than 1.0 m s^{-1}) by subtracting the estimated thermal effect given by Fig. 3 from the total pressure readings. The sample data were selected from the records for various months between November 1980 and March 1981 to cover a relatively wide range of temperature parameters. Figure 11 summarises the pressure differences in these cases plotted versus height.

The mechanical ventilation system has a relatively minor role in producing pressure differences across the walls. The magnitude of the contribution was found to be less than ±20 Pa, which is typically less than a quarter of the pressure difference caused by the stack effect*. The uncertainty in the prediction of the pressure difference due to the ventilation system is due mainly to the uncertainty in the estimates of the stack effect, which contributes more significantly to the total pressure difference. The other uncertainty concerns eqn. (1); since the heating and ventilation system affects the internal temperature distribution in the building, it may not be adequate to superimpose linearly the pressure difference caused by fan action on the estimated pressure differences due to natural ventilation alone.

Although attempts have been made to clarify the combination of these components in the past [10], verification of this point is still difficult.

Concluding remarks

Pressure differences across the external walls were measured on a 20-storey student residence building at the University of Ottawa. The wind velocity at the test building and the temperature distributions both inside and outside the building were also measured simultaneously.

The main findings of the preliminary analysis of the data are as follows.

(1) Pressure differences are caused by the stack effect, the wind and operation of the mechanical ventilation system. The first two causes are predominant for this particular building during the winter season.

(2) The stack effect, as for buildings having an open floor layout, is linearly proportional to the difference of the reciprocal outside and inside absolute temperatures, and varies almost linearly with height. The neutral pressure level occurs at ~70% of the total building height.

(3) The pressure distribution is also affected by the occupancy conditions of the building.

(4) The wind-induced pressure differences under relatively strong wind show good conformity with previous knowledge for typical bluff sections, such as a square. Because of the limited number of cases and test durations, the effect of the surrounding topography is not yet well understood.

(5) The pressure differences caused by the heating and ventilation system are much less in magnitude than those caused by the stack effect and by wind action. Evaluation of the former is still difficult.

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*The apparent increase of the NPL and the change in C_1 during "occupied" days were probably caused by the operation of the elevator-room exhaust fan located at the penthouse. As explained diagramatically in Fig. 6(b), the additional suction at the top of the building is responsible for this phenomenon.

Acknowledgements

Financial assistance for the present study provided by the Division of Building Research, National Research Council of Canada through a research contract (DSS No. OSU79-00296) is gratefully acknowledged.

The authors are grateful to Messrs. G. Spak, S. Law, P. Desnoyers and S. Lee for their participation in the study.

Acknowledgement is extended to Dr. C.D. Williams and the Low Speed Aerodynamics Laboratory of the National Aeronautical Establishment, National Research Council of Canada, for access to the wind measurement data.

Appendix I

Sample calculation of air infiltration

An example of the design calculation of air infiltration on the basis of measured pressure differences is given in this Appendix. The data required are as follows:

dimensions of walls (A) 4.34 m × 2.43 m = 10.76 m^2
dimensions of windows (A_2) 3.94 m × 1.37 m = 5.40 m^2
area of opaque walls (A_1) $A - A_2$ = 5.36 m^2
measured air leakage rates at Thompson Hall [1]
through opaque walls $(Q_1) = 0.020\,(\Delta P)^{0.91} \times 10^{-3}$ m s^{-1}
through windows $(Q_2) = 0.050\,(\Delta P)^{0.65} \times 10^{-3}$ m^2 s^{-1}
length of crack $(L) = 3.94 \times 2 + 1.37 \times 3 = 12.0$ m

The total infiltration rates Q, therefore, are given as follows:

ΔP (Pa)	20	40	60	80	100
$A_1Q_1 (10^{-3}$ m^3 s$^{-1})$	1.6	3.1	4.5	5.8	7.1
$LQ_2 (10^{-3}$ m^3 s$^{-1})$	4.2	6.6	8.6	10.4	12.0
$Q (10^{-3}$ m^3 s$^{-1})$	5.8	9.7	13.1	16.2	19.1

According to the conventional crack method [2],

$$Q = cA(\Delta P)^n \tag{5}$$

Therefore $n = 0.74$ and $cA = 0.63 \times 10^{-3}$ m^3 s^{-1} Pa^{-n}. The air infiltration rate through the exterior wall of one floor is given by

$$I = cA(\Delta P)^n \tag{6}$$

in which, neglecting $(\Delta P)_v$, as discussed in the penultimate section of the text,

$$\Delta P = (\Delta P)_s + (\Delta P)_w$$

Assume environmental conditions as follows:

outside temperature (T_o) = -20°C
inside temperature (T_i) = 25°C
wind speed at reference height (V_r) = 10 m s^{-1}
wind direction (θ) = 328° (building north)

then $\frac{1}{2}\rho(V_r)^2 = 70.0$ Pa, $C_1(1/T_o - 1/T_i) = 2.05$ Pa m^{-1}, and $C_2 = 39.1$ m.

From the results of preceding sections, taking the north wall, for example:

Floor	*3rd*	*8th*	*13th*	*18th*
Stack effect $(\Delta P)_s$ (Pa)	58	31	4	-23
Wind effect $(\Delta P)_w$ (Pa)	34	43	52	59
Total ΔP (Pa)	92	74	56	36
Infiltration rate I (10^{-3} m^3 s^{-1})	18	15	12	9

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