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WIND AND TEMPERATURE INDUCED PRESSURE DIFFERENTIALS AND AN EQUIVALENT PRESSURE DIFFERENCE MODEL FOR PREDICTING AIR INFILTRATION IN SCHOOLS

by C.Y. Shaw

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SOMMAIRE

Les différences de pression dues au vent ont été mesurées sur les murs extérieurs de 2 écoles, dont l'une est entourée de maisons et d'arbres et l'autre est partiellement protégée contre le vent. Ces écoles ont été choisies parmi 11 écoles dont les fuites d'air avaient été étudiées auparavant. Les différences de pression mesurées le long des murs ont été analysées et les taux d'infiltration de l'air correspondants ont été calculés. Ces taux ont été utilisés pour évaluer les différences équivalentes de pression uniforme causées par le vent. De même, les différences de même type dues aux cheminées ont également été calculées à l'aide d'un modèle par ordinateur. Il a été démontré que ces différences de pression équivalentes pouraient être totalisées puis utilisées, avec les données sur les fuites d'air obtenues par pressurisation au moyen d'un ventilateur, pour prédire les taux d'infiltration de l'air dans les écoles dans diverses conditions de vent et selon l'utilisation des cheminées.

No. 2573

WIND AND TEMPERATURE INDUCED PRESSURE DIFFERENTIALS AND AN EQUIVALENT PRESSURE DIFFERENCE MODEL FOR PREDICTING AIR INFILTRATION IN SCHOOLS

DR. C.Y. SHAW, P.Eng.

ABSTRACT

Wind induced pressure differences have been measured across the exterior walls of 2 schools; one is surrounded by houses and trees and the other is partially shielded from wind. These schools were selected from a total of 11 schools whose air leakage characteristics had been previously studied.

The measured pressure differences across the exterior walls were analyzed and the corresponding air infiltration rates were calculated. These were used to evaluate the equivalent uniform pressure differentials caused by wind. Similarly, the equivalent uniform pressure differentials caused by stack action were also calculated using a computer model. It was shown that these equivalent pressure differentials could be summed and used with the air leakage data obtained by fan pressurization method to predict air infiltration rates for schools under various conditions of wind and stack action.

INTRODUCTION

In the autumn of 1975, the Division of Building Research, National Research Council of Canada, was invited to participate with the Carleton Board of Education in a program to reduce energy use in their schools. Since air infiltration has always been recognized as one of the major factors affecting energy consumption of buildings, an air leakage study on schools was carried out. This study included the measurements of air leakage characteristics using the fan pressurization method[1] and pressure differences across the exterior walls caused by wind and stack action. These data provide a basis for calculating air infiltration rates for schools.

Air leakage tests conducted on 11 schools having various wall constructions and energy consumptions have been reported by Shaw and Jones[1]. Pressure differentials were subsequently measured on 2 of the 11 schools for a period of 8 months. In addition, a computer building model was used to calculate the pressure differentials caused by stack action. Finally, an equivalent pressure difference method for calculating air infiltration rates was derived from these results.

DESCRIPTION OF TEST SCHOOLS

Two schools as shown in Fig. 1 were selected for the study. School C is situated in a mature suburban residential area and is surrounded by houses and trees. School Q is also situated in a suburban residential area but is only protected by houses on the north and south sides. In addition, it is partially shielded from wind by another school on the west but is fully exposed on the east. The shapes of both schools are irregular as shown in Figs. 2a and 2b. A brief description of the 2 schools is given in Table 1.

C. Y. Shaw, Research Officer, Energy and Services Section, Division of Building Research, National Research Council of Canada, Ottawa, Ontario K1A 0R6.

PRESSURE DIFFERENTIALS MEASUREMENTS

Pressure differences across exterior walls were measured at 7 locations on the exterior walls of each school (Figs. 2a and 2b). All pressure taps in the walls facing the same direction were connected together so that an average reading was obtained. The pressure taps were drilled normal to the surface of walls at about mid-height. The reference pressure tap was located at the center of the main hallway of each school below the ceiling. These taps were connected to a scanner controlled by a scanner controller which was, in turn, driven by a multipoint millivolt recorder. A diaphragm-type pressure transducer with a static error band of 1.5% full scale output (500 mV at 10 V DC excitation) was used for pressure measurements. The output of the transducer was registered on a strip chart recorder. The time interval of each recording cycle which included readings of 7 pressure differentials, zero, and calibration was 4 min.

The pressure readings were taken with the air handling systems operating in both the day and night time modes. Its effect and that caused by stack action were removed by subtracting from the pressure data a base reading that was obtained when the wind speed was less than 2.3 m/s (5 mph). It was found that this base reading was strongly affected by the operation of the air handling systems and was almost insensitive to the daily variation of outside air temperature. The ranges of the base readings were found to be -7.5 to 0.75 Pa (-0.03 to 0.003 in. of water) for School C and 0 to 2.5 Pa (0 to 0.01 in. of water) for School Q.

On-site wind data were not taken; those recorded at the Division of Building Research (DBR) were used in the analysis. The height of the anemometer was about 15 m (49 ft) above ground. The distances between the DBR wind station and the 2 test sites were about 0.6 and 10 km (0.4 and 6 miles) for Schools C and Q respectively. It was found that the wind data collected at DBR were approximately equal to 84% of those recorded at the Ottawa International Airport (about 24 km or 15 miles away from DBR) for the same wind direction according to the 1977 weather data supplied by Environment Canada.

PRESSURE DIFFERENCE COEFFICIENTS

Fig. 3 shows a sample graph of pressure differentials as a function of wind speeds. Since the wind induced pressure differentials varied approximately with the square of wind speed as the fitted curve indicated, the measured pressure differentials were expressed in terms of pressure difference coefficients[2,3], C_{dpi}, defined as

$$C_{dpi} = \frac{2(\Delta P_i)}{\rho V^2} \tag{1}$$

where

ΔP_i = pressure difference across the ith wall, i = 1,2,3 and 4

ρ = air density

V = wind speed at 15 m (49 ft) above ground level

The values of C_{dpi} for the 2 schools shown in Fig. 4 were approximated by an equation of the form,

$$C_{dpi} = B_0 + B_1 \cos\Theta + B_2 \cos 2\Theta + B_3 \cos 3\Theta + D_1 \sin\Theta + D_2 \sin 2\Theta + D_3 \sin 3\Theta \tag{2}$$

where Θ is the wind angle from 0 to 360 deg for changes in the wind direction measured counter-clockwise from the true north. The coefficients for Eq 2 are given in Table 2.

AIR INFILTRATION CALCULATIONS

The rate of air leakage through the exterior walls of a building is given by the expression:

$$Q = C\,A\,(\overline{\Delta P})^n \tag{3}$$

where

Q = air leakage rate

C = flow coefficient

A = area of exterior wall

n = flow exponent

$\overline{\Delta P}$ = mean pressure difference across exterior wall

In order to use this expression it is necessary to know the appropriate values for C, n, and $\overline{\Delta P}$. The values of C and n for School C are 5.4×10^{-4}, $m^3/s \cdot m^2 \cdot Pa^n$ (3.8, cfm/ft^2 [in. of water]^n) and 0.65; for School Q: 4.8×10^{-4} (3.4) and 0.80, respectively. These values were determined from the results of fan pressurization tests. The roof leakage of School Q was not measured separately from the walls, so in this case it was necessary to get the wall component from the total leakage by comparing calculated and measured values of pressure difference distribution over the height of the walls due to stack effect alone. The roof leakage was varied in the computer building model[4] until the measured and calculated values of the pressure difference at different heights agreed. The air leakage rates through the exterior walls of the two schools are shown in Fig. 5.

When both C and n are known, the pressure differences caused by stack action can be calculated by solving the mass flow balance equations for each school using a computer model.[4] To account for the vertical variation of pressure differentials due to stack action, the leakage openings in each wall were assumed to be distributed vertically into 5 equal areas. The results were then combined with the wind induced pressure differentials[2,5] for calculating the total air infiltration rates from the equation

$$I = \sum_{i=1}^{4} \sum_{j=1}^{5} C\, A_{ij}\, k(\Delta P_{wi} + \Delta P_{sj})^n \tag{4}$$

where

I = air infiltration rate

C = leakage coefficient per unit wall area

A_{ij} = area of the jth level of the ith wall

ΔP_{wi} = pressure differential caused by wind across the ith wall; ΔP_{wi} is assumed to be identical vertically along each wall

ΔP_{sj} = pressure differential caused by stack action

n = flow exponent

k = 1 or 0 for positive or negative value in the bracket

DERIVATION OF AN EQUIVALENT PRESSURE DIFFERENCE MODEL FOR PREDICTING AIR INFILTRATION

In this paper, the term air infiltration is used to indicate the leakage of air into a building caused by wind and stack action; the term air leakage means the air flow obtained with a pressurization or suction test. The pressure differentials across the exterior walls vary from one wall to another for the infiltration condition but are uniform across all walls for the air leakage test. If the air leakage data obtained with an air leakage test is to be used for predicting air infiltration rates, an equivalent pressure differential representing the pressure differentials due to wind and stack action should be used as the $\overline{\Delta P}$ for calculating air infiltration rate from Eq 3. Hence, in the absence of stack action, equating the right-hand sides of Eq 3 and Eq 4, a uniform equivalent pressure differential caused by wind, ΔP_{we}, can be defined as

$$\Delta P_{we} = \left[\frac{1}{CA} \sum_{i=1}^{4} CA_i\, (\Delta P_{wi})^n \right]^{\frac{1}{n}} \tag{5}$$

Dividing Eq 5 through by velocity pressure, we have

$$C_{we} = \frac{2\Delta P_{we}}{\rho V^2} = \left[\sum_{i=1}^{4} \frac{A_i}{A} (C_{dpi})^n \right]^{\frac{1}{n}}. \tag{6}$$

where C_{we} is the equivalent pressure difference coefficient caused by wind. Its values are shown in Fig. 6 and can be approximated by the same expression as Eq 2. The appropriate coefficients for the two schools are also given in Table 2. Similarly, in the absence of wind, a uniform equivalent pressure differential caused by stack action, ΔP_{se}, is

$$\Delta P_{se} = \left[\frac{1}{CA} \sum_{i=1}^{4} \sum_{j=1}^{5} C\, A_{ij} (\Delta P_{sj})^{n} \right]^{\frac{1}{n}} \quad (7)$$

The values of ΔP_{se} are shown in Fig. 7. They can also be curve fitted to the form[2]

$$\Delta P_{se} = 117 \frac{(\beta H)^{1+n}}{1+n} \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \quad (8)$$

where β is the ratio of the height of the neutral pressure level and the building height, H. The value of β is 0.7 for both schools. Also, in Eq 8, ΔP_{se} is in pascals, H is in meters, T_i and T_o are inside and outside air temperatures in Kelvins. The constant 117 becomes 0.84 if the units change to inches of water for pressure differentials, feet for building height and Rankines for air temperatures.

Finally, a uniform equivalent pressure differential caused by the combined action of wind and stack action, ΔP_e, is obtained by adding the 2 pressure differentials together. Hence,

$$\Delta P_e = \frac{1}{2} \rho V^2 C_{we} + \Delta P_{se} \quad (9)$$

In Eq 9, C_{we} is based on the local wind speed. If the meteorological wind speed is used for V the values of C_{we} obtained from Fig. 6 should be multiplied by a factor of 0.7. The air infiltration, I, can now be calculated from Eq 3 which is rewritten as

$$q = \frac{I}{A} = C\, (\Delta P_e)^{n} \quad (10)$$

Eq 6,8,9 and 10 are the basic equations of the equivalent pressure difference model for predicting air infiltration rates. To use these equations it is necessary to know the appropriate values for C, n, β and C_{we}. The best way to determine these values is to measure them directly. This is not difficult to do as C, n and β are easily and accurately measurable. C_{we} can be calculated from Eq 1 and 6 using the pressure differences across the exterior walls measured during mild weather, but an estimate of C_{we} requires a large amount of data due to its variation with wind direction. However, a fairly good approximation of air infiltration rates may be obtained for design purpose from the following values.

	Class	$m^3/s \cdot m^2\ (Pa)^{0.65}$	$cfm/ft^2\ (in.\ of\ water)^{0.65}$
C	Tight	2.4×10^{-4}	1.7
	Average	4.0×10^{-4}	2.8
	Loose	5.6×10^{-4}	4.3
n	0.65 for all classes of construction		
β	0.7		
C_{we}	0.07 for protected site		
	0.15 for a more exposed site		

The values of C and n were based on air leakage data from 11 schools[1] (Fig. 8) where air leakage through walls was assumed to be 80% of the overall leakage (average of the two schools). The value of β was based on the data of the 2 schools; the values of C_{we} were also calculated from the results of the 2 schools with the effect of wind direction averaged (arithmetic mean of C_{we}).

DISCUSSION

The wind data used in this study were those measured at 15 m (49 ft) above ground at the Division of Building Research. A comparison of wind data between the DBR site and the meteorological weather station at the Ottawa airport indicated that the wind directions for both sites were almost identical. The wind speed at the DBR site, however, was about 84% of that at the airport site. In addition, based on the wind data collected over a period of a month, the wind at DBR was almost the same, both in direction and in speed, as that measured at a nearby site (anemometer height is about 18 m or 60 ft above ground) about 3km (1.3 miles) away from School Q. These comparisons appear to indicate that both the wind speed and direction in the vicinity of the DBR site enclosing the 2 schools are about the same.

The effects of air handling system and stack action were excluded from the pressure differential readings collected in winter by subtracting the base reading from them. For practical reasons, the base reading could only be established according to wind speed and the operation of air handling systems. Consequently, the effect of stack action might not always be excluded completely. Even so, this would not be expected to cause any appreciable error as evident by the agreement between the data collected in winter and summer (Fig. 3).

Pressure difference coefficients caused by wind are shown to be a function of wind angle. Their magnitudes, varying from one school to the other, were found to depend on wind direction and the amount of shielding by surrounding structures and trees. This can be observed from Fig. 6 which shows that the value of C for School Q is about twice as much as that of School C. This difference can also be partly attributed to the possible difference in the wind speeds at the 2 sites.

To give some indication of the magnitude of the air infiltration of the 2 schools, a sample calculation was performed using the Ottawa annual mean wind speed (4.5 m/s or 10 mph) and the mean outside air temperature of the 1976 heating season (-4°C or 25°F). It was found that the air infiltration rates at 0 deg wind direction were 0.3 air changes/hr for School C and 0.2 air changes/hr for School Q.

The infiltration rates were calculated assuming a uniform distribution of leakage openings and average pressure difference across each side based on readings of 1 or 2 pressure taps. The best way to verify these assumptions, and hence the proposed method, is to compare the calculated results with the field data using the tracer gas technique. There are some practical difficulties in applying this technique to large buildings such as schools. Until these difficulties e.g., imperfect mixing, are overcome the only verification that could be made is to check the validity of Eq 9, i.e., the assumption of adding the 2 pressure differentials together. This was made by comparing the calculated air infiltration rates with those obtained from Eq 4. The agreement as shown in Fig. 9 is within ±15% for various combinations of wind and stack effect.

The suggested values for β and C should only be used as an approximation as they were based on the results of 2 schools. On the other hand, a better estimate of these parameters might not be obtained even if additional data were available due to the difference in the shape, size, surrounding objects and orientation of each building.

SUMMARY

Continuous measurements of wind induced pressure differences across exterior walls were conducted for a period of 8 months on 2 schools having different building shapes and wind shielding conditions.

Using the measured pressure differentials, the air infiltration rates caused by wind were calculated and the corresponding equivalent pressure differentials were evaluated. Similarly, an equivalent pressure differential caused by stack action was calculated using a computer model. A method was developed for predicting air infiltration rates using the 2 equivalent pressure differentials and applying them directly to the air leakage values obtained from the fan pressurization or suction test.

NOMENCLATURE

A	total area of exterior walls
A_{ij}	area of the j^{th} section of the i^{th} wall; i = 1, 2, 3, and 4
C	flow coefficient per unit area of exterior walls; see Eq 3
C_{dpi}	pressure difference coefficient caused by wind for the i^{th} wall; see Eq 1 and 2.
C_{we}	equivalent pressure difference coefficient caused by wind; see Eq 6
I	air infiltration rate; see Eq 4
n	flow exponent; see Eq 3
$\overline{\Delta P}$	uniform pressure difference across a building enclosure induced by an air leakage testing fan; see Eq 3
ΔP_e	uniform equivalent pressure difference across a building enclosure caused by combined action of wind and stack action; see Eq 9.
ΔP_i	pressure difference across the i^{th} wall
ΔP_{se}	uniform equivalent pressure difference across a building enclosure caused by stack action; see Eq 7 and 8
ΔP_{sj}	pressure difference across exterior walls at the j^{th} level caused by stack action
ΔP_{we}	uniform equivalent pressure difference across a building enclosure caused by wind; see Eq 5
ΔP_{wi}	pressure difference across the i^{th} wall caused by wind
q	air infiltration or air leakage rate per unit area of exterior walls; see Eq 10
Q	air leakage rate
T_i	absolute inside air temperature
T_0	absolute outside air temperature
V	wind speed at 15 m (49 ft) above ground
β	ratio of height of neutral pressure level and building height
θ'	wind angle measured counterclockwise from the true north
ρ	air density

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ACKNOWLEDGEMENT

The author is indebted to the Carleton Board of Education for cooperation in making this study possible. He gratefully acknowledges, also, the contribution of D.G. Stephenson and G.T. Tamura in the preparation of the paper and the assistance of R.G. Evans and R. Plouffe in taking the field measurements.

This paper is a contribution of the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

TABLE 1

Description of Test Schools

School		C	Q
Year Tested		1977	1977
Year Constructed		1972	1968
Floor Area, m^2 (ft^2)		3003 (32331)	3219 (34650)
Floor Height, m (ft)		4 (13.0)	3.8 (12.5)
Volume, m^3 (ft^3)		11900 (420303)	12263 (433125)
a. Exterior Wall Area m^2(ft^2)	side 1	341 (3671)	500 (5382)
a. Exterior Wall Area m^2(ft^2)	side 2	341 (3671)	486 (5231)
a. Exterior Wall Area m^2(ft^2)	side 3	341 (3671)	486 (5231)
a. Exterior Wall Area m^2(ft^2)	side 4	341 (3671)	343 (3692)
a. Exterior Wall Area m^2(ft^2)	Total	1364 (14684)	1815 (19536)
Window Type		Fixed Sealed Domes, Fixed & Openable Sealed Double Glazing	Fixed Sealed Domes, Fixed & Openable Sealed Double Glazing
Window Area/Wall Area		0.062	0.102
Openable Window/Wall Area		0.008	0.040
Typical Wall Construction		10.2 cm Split Black Face 5.1 cm Air Space 15.2 cm Conc. Blk & Foamed in Place Insul	10.2 cm Face Brick 5.1 cm Foamed Insulation 20.3 cm Conc. Blk
No. of Exterior Doors	Vestibule	3 sgle, 2 dble	14 sgle, 1 dble
No. of Exterior Doors	No Vestibule	2 sgle, 3 dble	6 sgle
HVAC System		Gas Centralized All Air H/V Systems with Roof-Top A.H. Units	#2 oil & Elect Centralized All-Air H/V System with convector or unit ventilator in Perimeter Room

Notes: a. Including Window

TABLE 2

Coefficients for Evaluating C_{dpi} and C_{we} using Eq. 2

		C_{dpi}				C_{we}
	Exterior Wall	Side 1	Side 2	Side 3	Side 4	
School C	B_0	0.06493	0.11563	0.04419	0.02645	0.06764
	B_1	0.11472	0.00595	-0.19072	0.07389	0.00036
	B_2	0.03352	-0.03642	0.04148	-0.02562	-0.00012
	B_3	0.00449	0.01863	0.01895	0.00107	0.01234
	D_1	-0.10454	0.18646	0.0429	-0.22104	-0.00892
	D_2	-0.00632	0.0094	0.01859	0.01064	-0.00709
	D_3	-0.00759	0.02089	-0.04682	-0.01982	-0.00459
School Q	B_0	0.02715	0.15246	0.16863	0.22315	0.1514
	B_1	0.28057	-0.20325	-0.24845	0.17389	-0.1517
	B_2	0.15203	-0.07877	-0.03032	-0.04746	0.01928
	B_3	0.05197	-0.05512	-0.05965	0.0512	0.00891
	D_1	0.01285	0.24718	-0.09662	-0.36168	-0.010
	D_2	0.07918	-0.06608	-0.01192	-0.01675	-0.01076
	D_3	0.04136	-0.00877	-0.01782	-0.04668	-0.0006

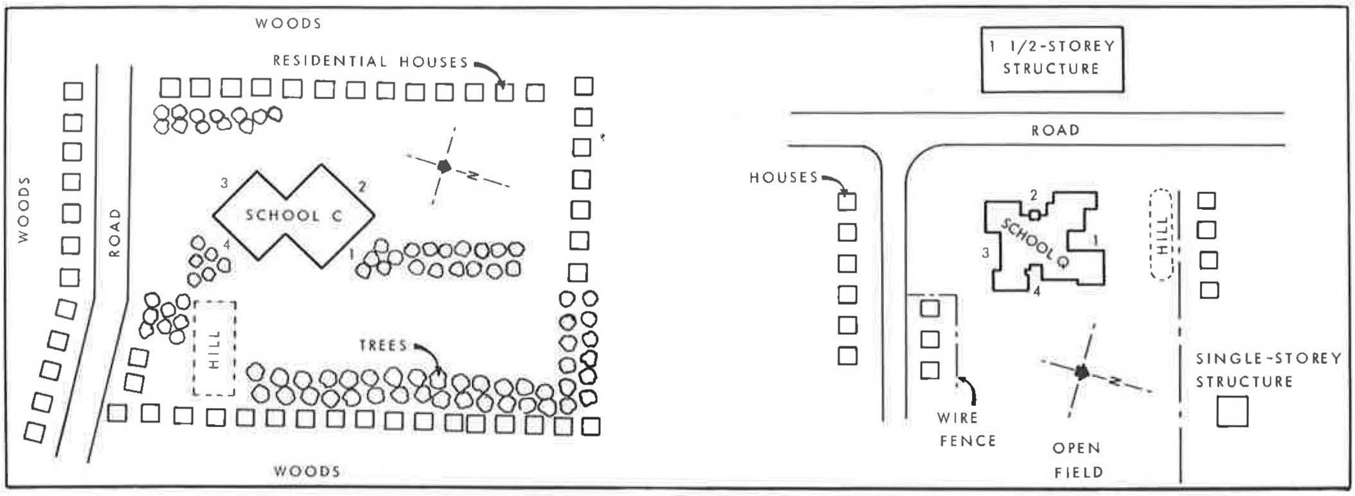

Fig. 1 Test sites

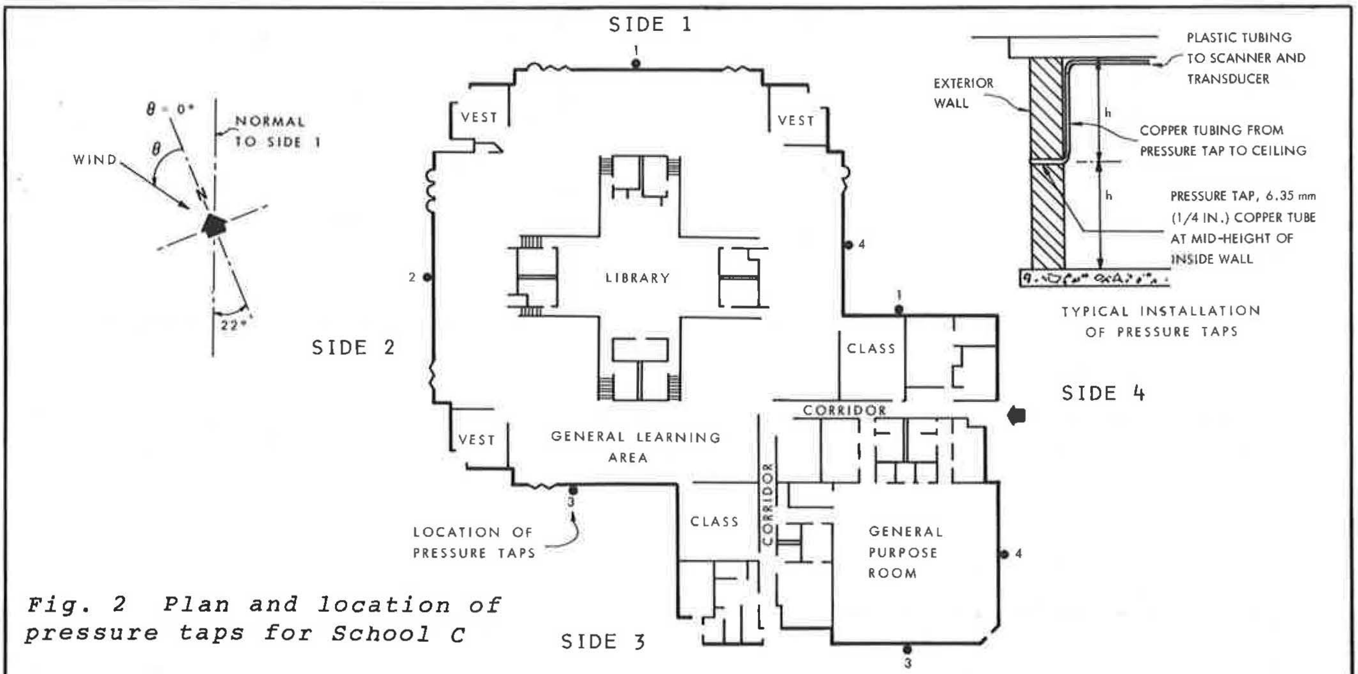

Fig. 2 Plan and location of pressure taps for School C

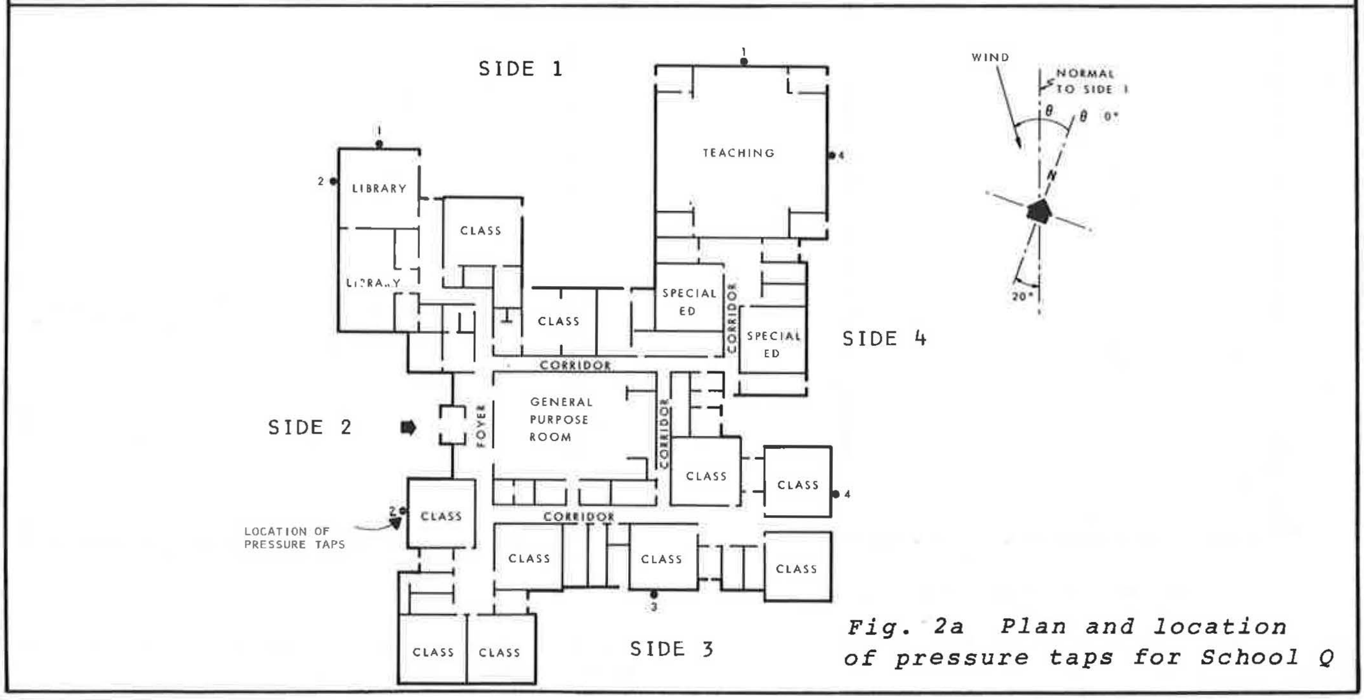

Fig. 2a Plan and location of pressure taps for School Q

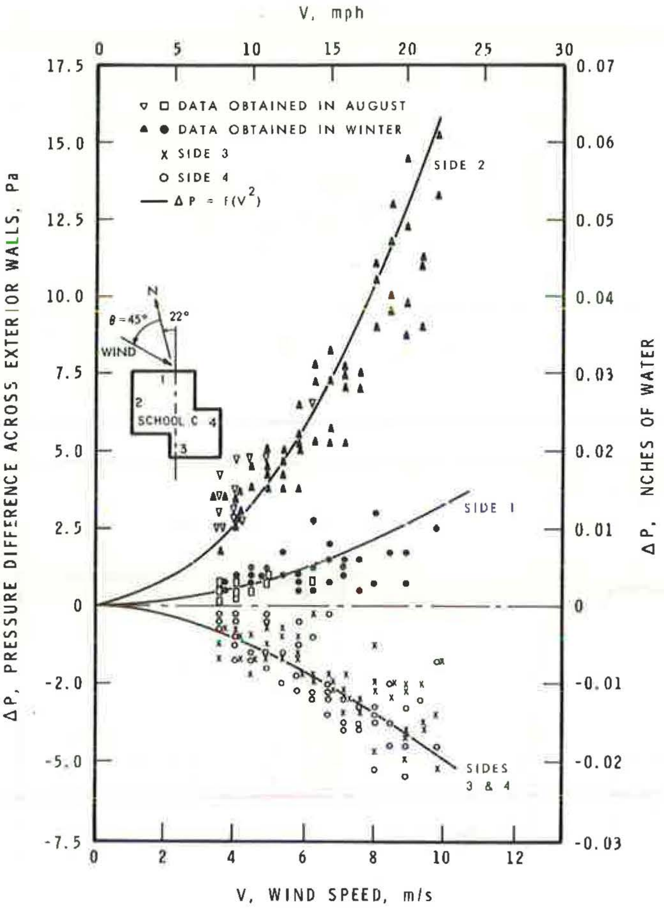

Fig. 3 Sample graph showing pressure differentials as a function of wind speed

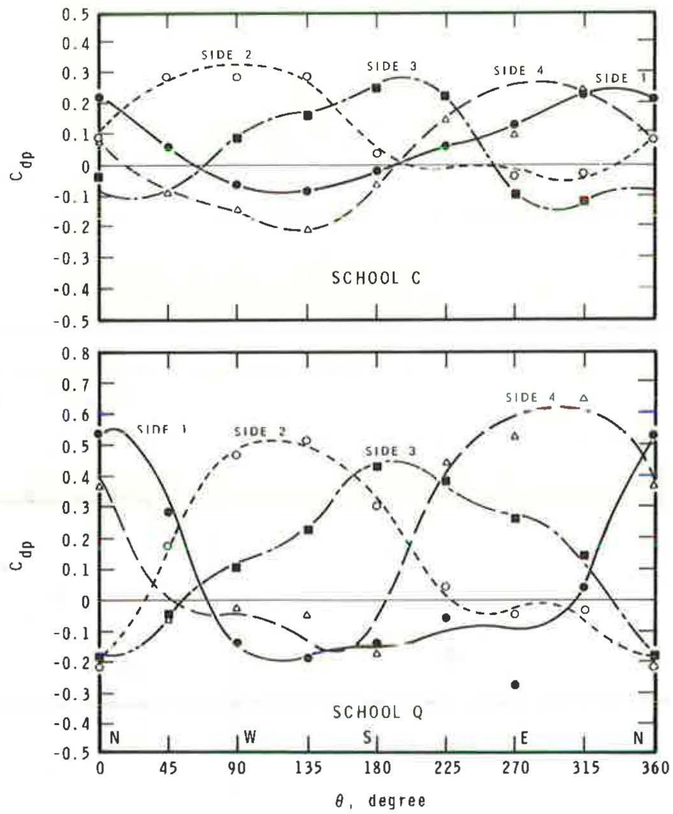

Fig. 4 Wind induced pressure difference coefficients vs wind direction

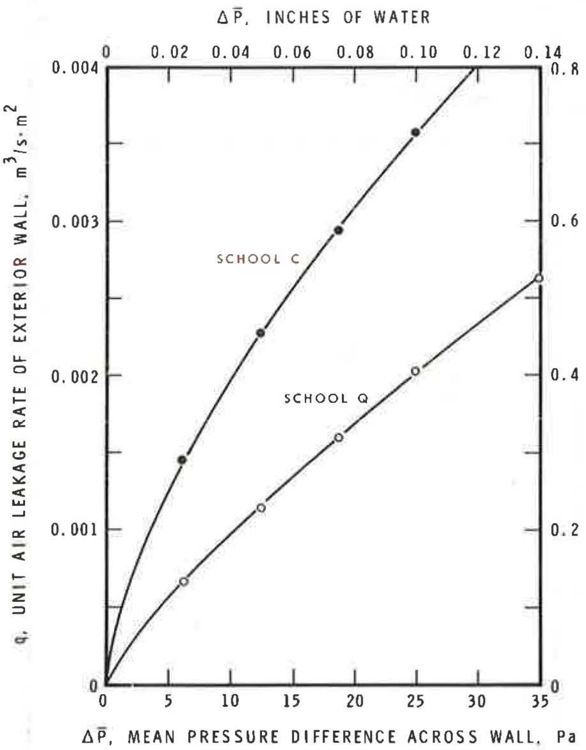

Fig. 5 Air leakage rates through exterior walls

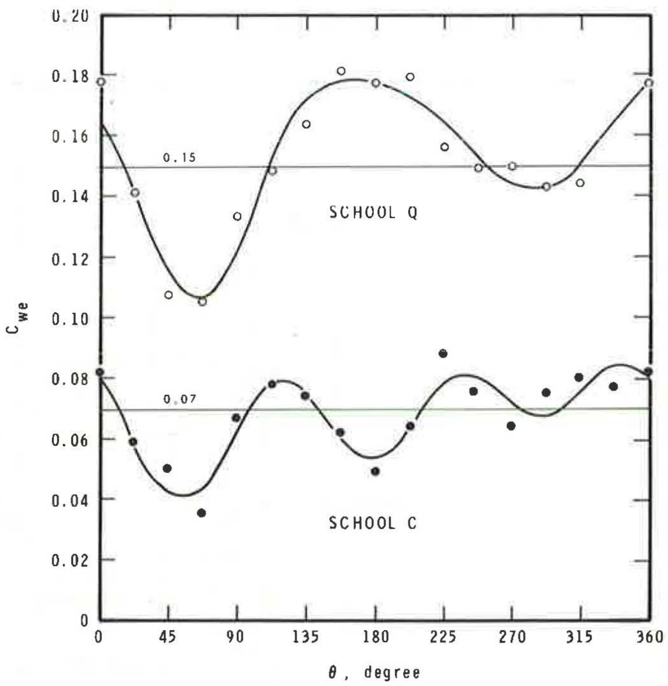

Fig. 6 Equivalent pressure difference coefficients due to wind

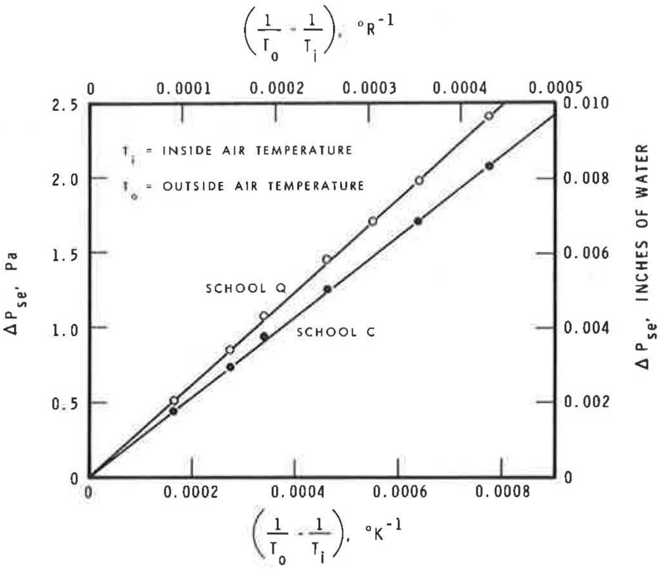

Fig. 7 Equivalent pressure differentials due to stack action

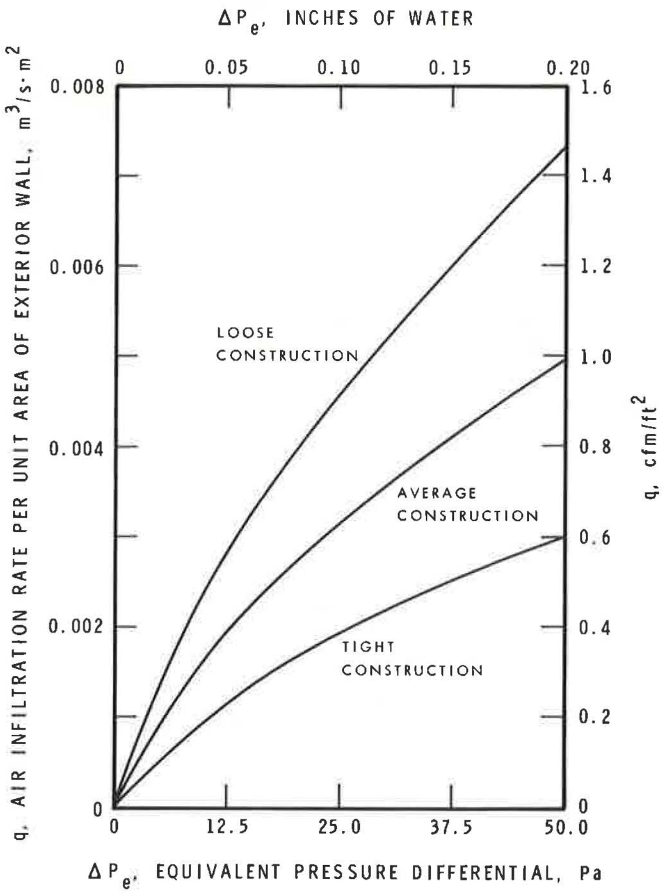

Fig. 8 Generalized air infiltration rates for schools

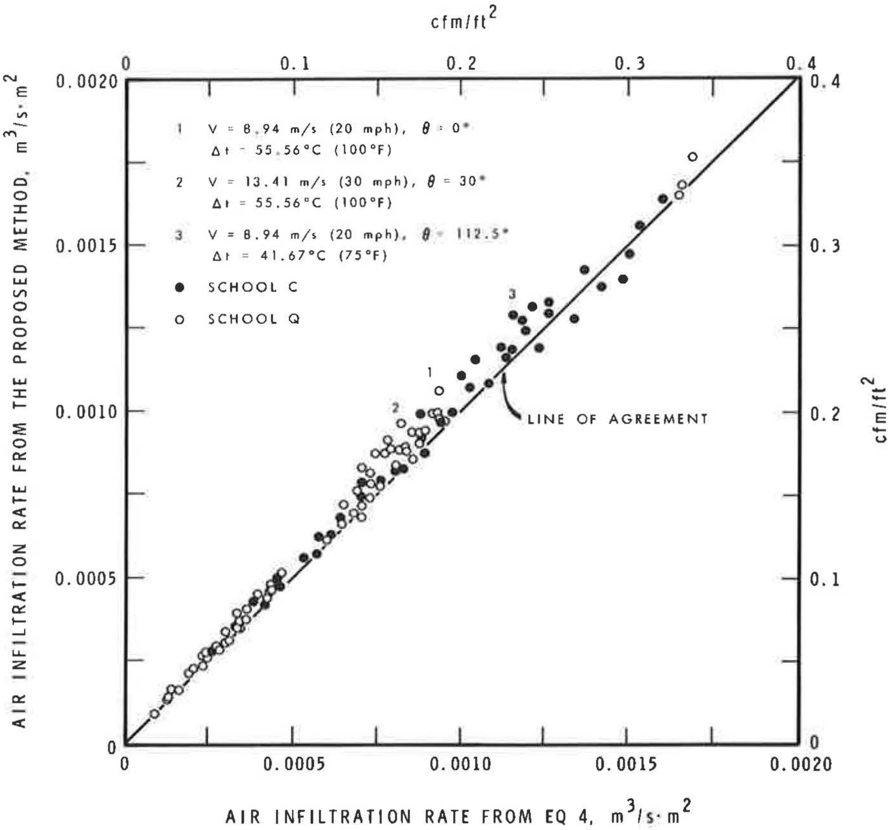

Fig. 9 Comparison of calculated air infiltration rates using Eq 4 with those using the proposed method

DISCUSSION

JAMES E. GRIFFITH, Sr. Resch. Engr., PSE&G Resch. Corp., Maplewood, NJ: Were test data taken throughout the year or only in the summer?

C.Y. SHAW: The wind pressure differentials were taken for a period of 8 months.

W. RUDOY, Prof., Univ. of Pittsburgh, Pittsburgh, PA: Would you care to comment on the value of air changes of 0.2 to 0.3 air changes per hr as reported in the paper. This appears to be low compared to other values reported in the literature for buildings.

SHAW: The air change rates given in the example are the predicted air infiltration rates due to the combined action of wind and stack effect. They do not include the amount of infiltration caused by the operation of the building air handling system which cannot always be excluded from the infiltration measurements conducted at the site.