Natural Wind Effects on the Infiltration of Low-Rise Buildings

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Summary

Conservation of energy, ventilation need and insulation effectiveness considerations have increased the public awareness of the significance of building infiltration. The present paper examines the effect of wind pressure distribution on the infiltration of low residential and industrial buildings of various geometrical configurations, wall openings and permeability. Internal pressures of scaled building models have been measured in a boundary layer wind tunnel for various wind directions and two roughness conditions representing an open country and a suburban terrain. A computer program has also been developed, which calculates internal pressures and infiltration rates at external building walls, and the results agree with the experimental measurements reasonably well. Air flow rates have also been compared with experimental data from previous studies, and the importance of the use of a correct wind pressure distribution has been shown. Comparisons with the Canadian, American and Swedish Standards have indicated that more parameters have to be incorporated for the determination of infiltration of low-rise buildings.

Resumé

Les considérations sur la conservation de l'énergie, la nécessité de ventilation et l'éfficacité de l'isolation ont accru la conscience du public sur la signification de l'infiltration dans les bâtiments. Cet article étudie l'effet de la distribution de la pression du vent sur l'infiltration dans des bas bâtiments résidentiels et industriels ayant différentes configurations géométriques, ouvertures de murs et perméabilitée. Les pressions intérieures des quelques bâtiments modèles ont été mesurées en soufflerie simulant le vent naturel dans différentes directions de vent et dans deux conditions turbulentes représentant un terrain ouvert et un terrain suburbain. Un programme au calculateur a aussi été développé, qui calcule les pressions intérieurs et les vitesses d'infiltration aux murs extérieurs des bâtiments, et les résultats coincident assez bien avec les expériments. Les vitesses de coulement de l'air ont été aussi comparées avec les données expérimentaux obtenues dans des recherches antérieures et aussi a été demontrée l'importance de l'utilisation d'une distribution correcte de la pression du vent. Les comparaisons avec les standards canadiens, américains et suédois ont indiqué qu'il faut tenir compte de plusieurs paramètres pour déterminer l'infiltration dans les bâtiments de faible hauteur.

1. Introduction

Whereas conservation of energy is the subject of central interest in the world nowadays, not enough information is available regarding heat gains and losses from buildings and wind-generated natural ventilation of housing. In reality, a building may have considerable inherent leakage, as well as the potentiality for large openings due to the presence of doors or windows. As a result, internal pressures and infiltration rates in various building configurations due to wind action may vary drastically.

Although the significance of internal pressures is well recognized, not only for energy considerations but also for structural applications in the wind loading problems, very few studies have dealt with it. Among those that have, only one or two are either full-scale cases or model cases in appropriate atmospheric simulations. A study [1], recently completed, deals with the determination of internal pressures in low residential and industrial buildings with various uniform porosities combined with different wall openings. The present paper compares some of the experimental results of this study with analytically predicted values of internal pressures, and provides data of infiltration rates. Due to the lack of sufficient data on these topics, only limited comparisons with others' findings can be made.

2. Experimental Methodology; Building Models

The experimental measurements have been carried out at the Boundary Layer Wind Tunnel of the University of Western Ontario. The tunnel has a working section about 80 ft long, 8ft wide and 7 ft high. Most of this fetch is required for the natural production of a boundary layer which grows in a manner paralleling the atmospheric process under neutral conditions. The surfaces in the wind tunnel can be changed to represent different terrains. For the tests reported here, two terrain models have been used representing open country and suburban conditions. A picture of the wind tunnel with a model placed at the test section is shown in Fig. 1.

Three basic 1:250 scale models were constructed, all providing variable side-wall and end-wall openings and three background porosities of 0%, 0.5% and 3% of the total surface area. All models are sealed underneath. The two "small" models represent 80 x 125 ft buildings with 1:12 and 4:12 roof slopes. The "large" model, shown in Fig. 2 diagrammatically, represents a building geometrically similar in plan and having 2.5 times the plan dimensions. The small models could be tested at 16, 24 and 32 ft eave heights, whereas the large model could be tested only for a 32 ft eave height. The background porosity or permeability of the envelopes of models was achieved by twelve rows of circular holes of two different sizes. These small and large holes were evenly distributed in three zones (at the middle and both ends of each wall and the roof) and were left open or closed in various symmetrical combinations so that

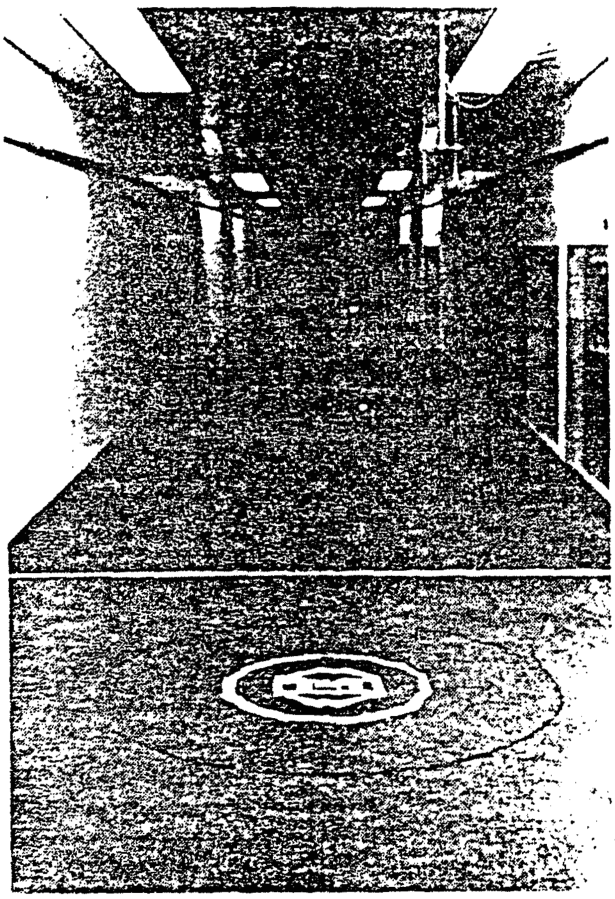

Fig. 1. The Boundary Layer Wind Tunnel of the University of Western Ontario with the Small Model at the Test Section.

a uniform permeability could be attained. Although this simulates porosity in a manner somewhat different to reality, local effects were found to be small, and hence for pressure measurements at locations, a reasonable distance from the holes, the difference is not likely to be significant. The chosen values of background porosity ratios (0-3%) appear to include most cases of practical interest.

All models are equipped with pressure taps on both the internal and external surfaces. Each tap is connected to a pressure transducer through a length of plastic tubing 1/16" I.D., which contains a restrictor to optimize its frequency response characteristics. Scaling and similarity requirements for wind tunnel determination of external and internal pressures have been discussed in detail in references 1 and 2. Such similarity considerations lead to the determination of velocity and time scales of the order of 1:10 and 1:100 respectively, for typical full-scale design speeds. The

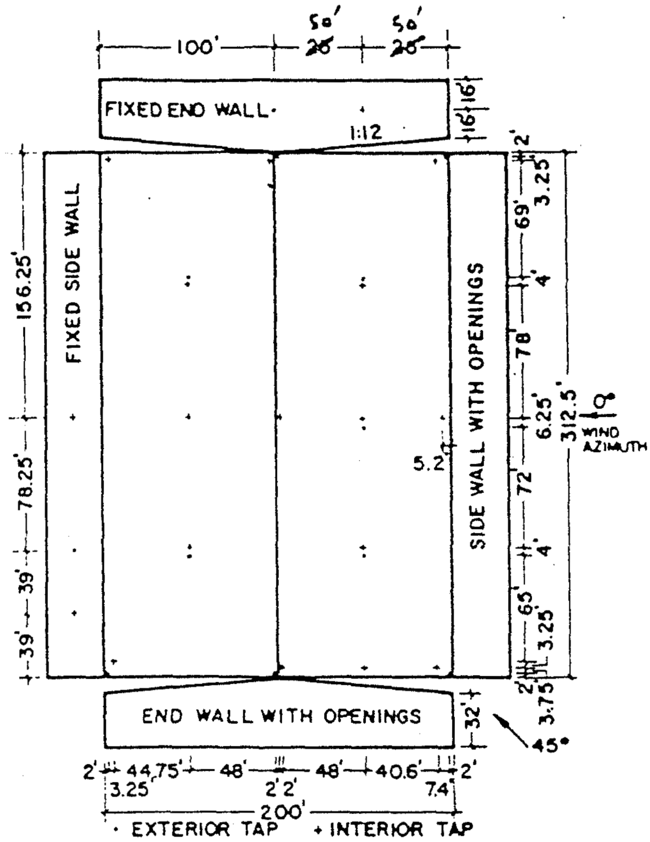

Fig. 2. Exploded Plan View of the Large Model Showing the Position of Pressure Taps.

air speed in the wind-tunnel above the boundary layer is about 45 ft/sec.

3. Analytical Predictions

Under steady conditions of external pressures acting on the building envelope, the air entering a building should balance the air leaving the building. Thus, internal pressures depend on the external pressure distribution and the air-leakage characteristics of a building. Internal pressures for all building configurations of this study have been calculated as follows :

Each of the six faces of the building envelope (four walls, windward roof side and leeward roof side) has been divided into three parts, for each of which the air-leakage equation [3] can be written as :

$$q_j = \pm CA_j(|\bar{P}_{e,j} - \bar{P}_i|)^n \qquad (1)$$

in which q_j is the air leakage per unit time for the j^{th} part; C is a constant of proportionality; A_j is the open area of the j^{th} section; $\bar{P}_{e,j}$ is the mean external pressure at the j^{th} part; $\bar{P}_i$ is the mean internal pressure; and n is the flow exponent. The sign in the right-hand side of Eq. 1 indicates the direction of the flow. A positive sign has been used for inward air leakage.

In the fully-developed turbulent flow, a value of 0.6 is commonly used for the proportionality constant C, and a value of 0.5 for the flow exponent. As the flow becomes less turbulent, both C and n increase and approach unity in the case of laminar flow. Full-scale measurements in buildings [4,5] indicate values of n ranging between 0.5 and 0.8. In the present work, three combinations of values for C and n parameters have been used, namely :

C	n
0.6	0.5
0.8	0.667
1.0	1.0

The air balance equation

$$\sum_j q_j = 0 \quad (2)$$

has then been formulated by using external pressure measurement results and has been solved numerically through a computer program to yield the internal pressure $\bar{P}_i$ for each building configuration and terrain roughness.

After this calculation, equation 1 was used to derive the air leakage per unit time for each section. The total building infiltration rate was then found by considering the algebraic sum of all partial air leakages. Results have been expressed in the well-known air change number form by dividing the total air leakage with the building volume for each case.

4. Results and Discussion

Pressure measurement and calculation results have been expressed in coefficient form as :

$$C\bar{p}_e = \frac{\bar{P}_e - P_o}{\frac{1}{2}\rho \bar{V}_E^2}, \quad C\bar{p}_i = \frac{\bar{P}_i - P_o}{\frac{1}{2}\rho \bar{V}_E^2} \quad (3)$$

in which $\bar{P}_e$ and $\bar{P}_i$ are mean external and internal pressures respectively; P_o is the static pressure of the free stream outside the boundary layer height; $\bar{V}_E$ is the mean wind speed at eave height; and ρ is the air density.

The principal highlights of the experimental measurements and analytical results can be summarized as follows :

i) External pressure coefficients have been found insensitive to both background porosities and wall-opening ratios. It is expected, however, that external pressure distribution will be affected in cases for which the configuration of the openings permits large flows through the building.

ii) Internal pressures fluctuate significantly, but their overall magnitudes are generally less than that of the local external pressures. The overall gust factor - the ratio of peak pressure to the mean - is roughly two in open country exposure.

iii) The fluctuations in internal pressure show little or no spatial variation, except in regions close to dominant openings. This is illustrated in Fig. 3 where typical time traces of pressures from two internal taps located at opposite ends of the large building are shown. The traces are virtually identical. This characteristic is quite general for all various configurations examined and leads to the conclusion that properties of the internal pressure can be given without reference to the particular location within the building.

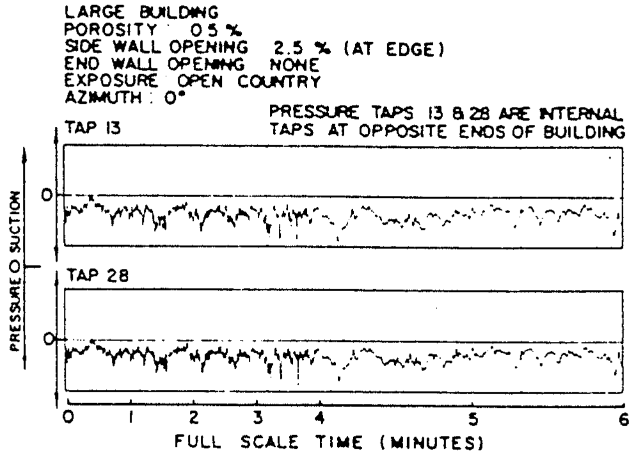

Fig. 3. Simultaneous Time Traces of Internal Pressures for Two Different Taps.

iv) A high correlation between external and internal pressures has been found in all cases.

v) Largest internal pressures occur when the wind direction is perpendicular to the wall with dominant openings.

vi) For windward openings, although internal pressure coefficients are generally positive, cases with high background porosity combined with small openings produce zero, or slightly negative coefficients. Typical results of measured and analytically predicted mean internal pressure coefficients are shown in Fig. 4 for both larger and smaller building models. It can be seen that for wall openings of significant size (more than 50% of the wall area) the internal pressure coefficients become essentially independent of the background porosity. The lower the background porosity, the smaller the necessary size of the wall opening needed to make the internal pressure coefficients insensitive to further increases of the wall opening.

The analytically predicted values of $C\bar{p}_i$, shown also in Fig. 4, agree well with the experimental results. Calculated internal pressure coefficients have been found by using $C = 0.8$ and $n = 0.667$. Very similar results, however, have been obtained by using other combinations of C and n values referred to in section 3. For instance, in the case of fully turbulent flow, $C\bar{p}_i$ values were found slightly higher, the largest difference being 0.02; in the case of laminar flow $C\bar{p}_i$ values were a little lower, the largest difference

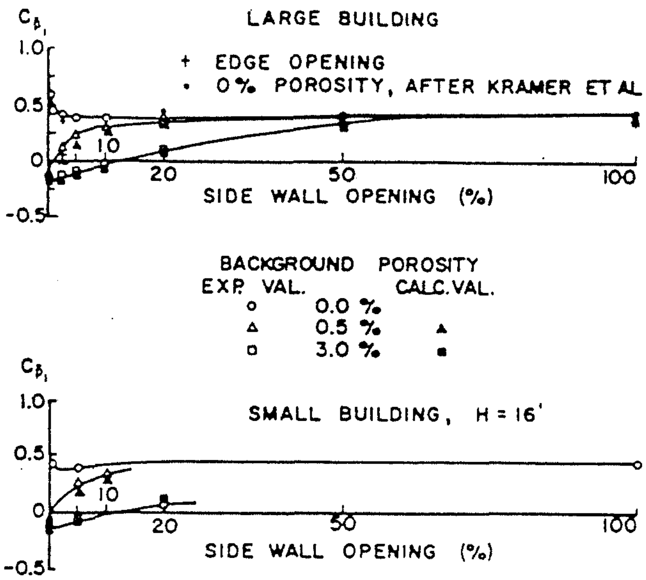

Fig. 4. Measured and Predicted Mean Internal Pressure Coefficients for Various Side Wall Openings and Background Porosities - No End Wall Opening, 1:12 Roof Slope, Open Country Exposure, 0° Azimuth.

found was 0.06. The above comparisons show that model building internal flows have a rather dominant turbulent character.

In the case of 0% background porosity, experimental measurements show that internal pressure coefficients have a constant value, that of external wall pressure coefficient for all different side wall openings. Some increase of $\bar{Cp}_i$ values appears for very small wall openings, but this is perhaps due to experimental inaccuracies since the slightest leakage between the model and the outside of the wind tunnel may contaminate the data under conditions approaching nominal building impermeability. Experimental results from a study carried out by Kramer et al [6] for an impermeable model building with 20% side wall opening agree very well with the present data. No significant difference has been noticed as far as the internal pressure coefficients measured or calculated for the larger and smaller buildings.

vii) When the dominant openings are at the rear of the building, and the windward wall is closed (azimuth 180°), the internal pressures are generally negative and are not very sensitive to the size of wall openings or to the background porosity. Typical results are presented in Fig. 5 for measured and calculated $\bar{Cp}_i$ values for all configurations of the tested large building. The largest negative $\bar{Cp}_i$'s are almost equal to the external pressure coefficients measured on the leeward walls. Again, a good agreement between measured and calculated values is apparent.

viii) Infiltration rates have been found very sensitive

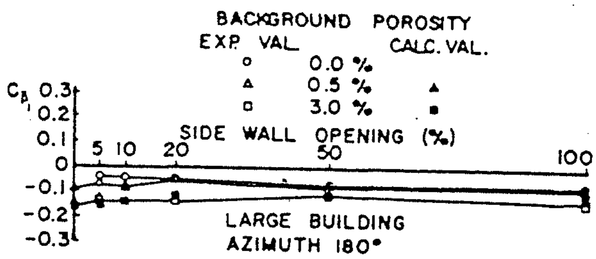

Fig. 5. Measured and Predicted Mean Internal Pressure Coefficients for Various Side Wall Openings and Background Porosities - No End Wall Opening, Open Country Exposure, 180° Azimuth.

to internal pressure variation.. Air change numbers have been calculated by using the internal pressure predicted and the procedure explained in section 3. Results are presented in Fig. 6 for two background porosities and both 0° and 180° azimuths for a mean wind speed of 10 ft/sec at building eave height. In case of windward openings, the higher the background porosity, the higher the necessary opening ratio to make the air change number insensitive to further increase of openings. In contrast, for leeward openings, the air change number remains almost constant for each permeability regardless of the wall opening. The latter has been predicted since internal pressures have values very similar to the external wind pressures on the leeward wall for all opening ratios.

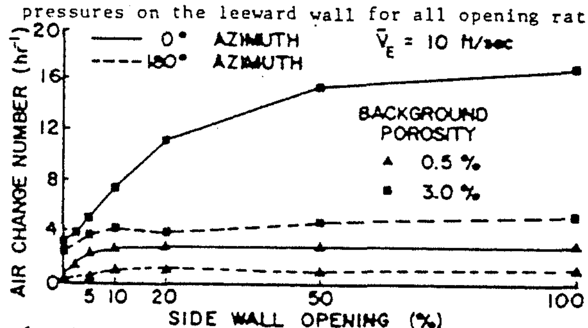

Fig. 6. Air Change Number Predicted for Various Side Wall Openings and Background Porosities - No End Wall Opening, Large Building, Open Country Exposure.

ix) For higher values of background porosity, the air change number varies drastically with wind speed variation, whereas for small building permeabilities air change number remains almost constant. Figure 7 shows the variation of air change number in the case of large building with no wall openings. Data have been calculated for various permeabilities ranging from 0.01% to 0.5% and for wind speeds at eave height up to 40 ft/sec, since these are the cases of main practical interest. For typical permeability values of well-insulated buildings, the air change number is very low.

x) Although internal pressure coefficients have been found significantly higher for the suburban exposure, the actual internal pressures and, consequently, infiltration rates are not very different

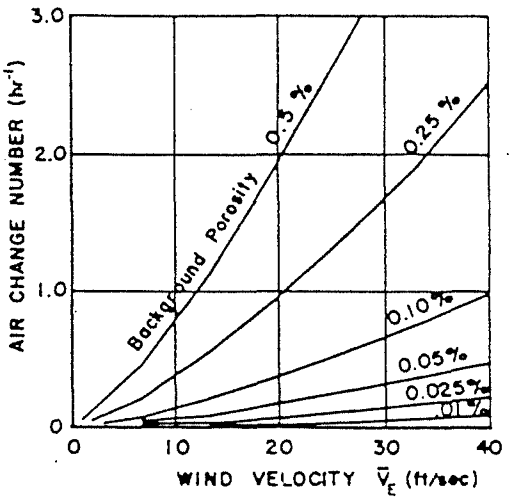

Fig. 7. Background Porosity Effect on Air Change Number-No Wall Opening, Large Building, Open Country Exposure, 0° Azimuth.

from those calculated for the open country exposure. This is due to the reference velocity at eave height which is significantly lower in the case of suburban exposure. As a result, air change numbers given in this paper can be considered representative of various terrain roughnesses.

5. Applications - Comparisons with Codes and Standards

Roofs of low-rise buildings have, in general, larger areas than external walls. Given that the highest wind suctions dominate on flat or low-sloped roofs, significant air exfiltration may take place through small cracks, skylights, etc. there. It has been found that in cases of no sufficient openings in the windward wall, infiltration may occur in the leeward wall of a low building. The latter is normally neglected in most standards, but it may affect the heating and air-conditioning load of leeward spaces of low buildings.

A direct comparison between standards, codes of practice of different countries and the present results cannot be carried out since infiltration rates depend not only on the wind action but also on temperature differences (stack or buoyancy effect). The Canadian Code [7] suggests for mechanically ventilated residential buildings a minimum of 1 ac/hr, whereas Swedish specifications recommend a minimum of 0.5 ac/hr [8]. American standards [3] specify minimum and recommended values (the latter are about 50% higher than the former) for buildings serving different purposes. Minimum values, however, range up to 10 ac/hr. If the Canadian requirement has to be satisfied only by wind-caused natural ventilation Fig. 7 shows that for wind speed of 10 ft/sec at eave height, a porosity higher than 0.5% would be needed (assuming that all openings are closed). This is a rather high value when compared to permeability measurements of typical Canadian houses carried out by Tamura [4] indicating values ranging between 0.02% and 0.09%. It is important, however, to consider the stack effect in the calculation as well.

A recent study by Peterson [9] based on the statistical analysis of infiltration measurements for typical Canadian and American dwellings, suggests values of 0.1 ac/hr for tightly constructed houses and 0.2 ac/hr for loosely constructed houses. These values have been calculated for wind speed of 10 ft/sec at eave height under the assumptions that all openings are closed and that inside and outside temperatures are equal. Results of the present study for the 16' high small building, which corresponds to the average geometry of buildings considered in Peterson's study, have led to values of 0.12 ac/hr for tightly constructed houses and 0.45 ac/hr for loosely constructed houses. Again, the stack effect has to be considered to attain values corresponding closer to reality.

6. Conclusions and Recommendations

In summary, the following conclusions can be made :

i) Mean internal pressures measured in the wind tunnel agree well with analytically predicted values calculated by using external pressures and typical air leakage constants. Internal flow simulation also appears to be adequate.

ii) Accurate evaluation of internal pressures is necessary to calculate building air infiltration.

iii) For low-rise industrial buildings, air exfiltration from the roof appears to be very large and infiltration may occur through all four walls.

It is suggested that further experimental work be carried out by measuring internal pressures in model buildings with horizontal and vertical partitions for the evaluation of air flow patterns inside low buildings. These patterns affect strongly the ventilation efficiency of these buildings. Also, as long as temperature stratification inside buildings cannot be avoided, it appears that the energy efficiency of the building depends not only on the infiltration effect, but also on the temperature of the exfiltrated air. Further study is required on the interaction between wind and stack action and their effect on the performance of mechanical ventilation systems.

7. References

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