Predicting Natural Ventilation Forces Upon Low-Rise Buildings

This paper describes a series of wind tunnel investigations which have led to the development of a procedure by which it is possible to estimate the wind pressure forces that act on a low-rise building which is part of a large group of similar buildings. The use of this technique makes it possible to allow for the building form, the parameters which describe the group in which it is situated, the upstream building conditions, and the direction of the wind.

B.E. LEE
M. HUSSAIN
B. SOLIMAN

WHILE the assessment of the natural ventilation rates of low-rise buildings is an area of growing concern in the continued search for greater interior comfort standards, this concern is perhaps reflected more in our awareness of the energy impact which this source of heat loss has on the present financial climate. It is surprising therefore that so little is known about air infiltration in the low-rise buildings, which continue to comprise the majority of our housing stock. The relatively small amount of data which exists relates only to isolated buildings, despite the fact that other spheres of fluid mechanics have for some time recognized the importance of proximity effects in the prediction of fluid flow phenomena.

Building design must be accomplished within both economic and environmental constraints. As part of this design process, natural ventilation is often found to be the only means available to the designer for supplying fresh outside air into building interiors where the external climatic impacts are not too severe. Therefore, a proper estimate of the natural ventilation rates in buildings is necessary if buildings are to meet both their environmental and economic requirements.

The crack method for natural ventilation rate calculation, described in the ASHRAE Handbook and Fundamentals (1972) is based in principle on the following equation which relates the ventilation rate, Q, to the pressure difference, Δp_o, acting across any opening

$$Q = C_i \cdot L_c (\Delta p_o)^{1/n}$$

B.E. Lee is with the University of Sheffield, UK; M. Hussain is with Lahore University of Engineering and Technology, Pakistan, and B. Soliman is with Ashute University in Egypt.

For a particular building, the infiltration coefficient, C_i, the exponent n, and the crack length L_c, are dependent on the type and the area of the openings. Δp_o remains to be determined in order to obtain the ventilation rate, Q.

From the work on air flow round building models, an estimate of the mean pressure difference across the building Δp, may be obtained, half of which is assumed to act across each of the windward and the leeward faces of the building, giving Δp_o. It appears that the main assumption made in the guides for the estimation of Δp may result in considerable error. A number of important factors affecting its magnitude are neglected where these factors include definitions of the building form and the properties of the oncoming flow.

The pressures which govern the value of Δp are determined by the process of separation and reattachment of air flow round the body. Although the factors affecting the separation are not necessarily the same as those affecting reattachment, it seems logical to classify all the factors involved into the following two groups

(1) factors related to the building form, and

(2) factors related to the properties of the wind.

In the case of low building density where buildings are wide apart, e.g., in open country, the individual building form is the only form that the wind can 'see.' As the density increases, e.g., in suburban and urban areas, buildings are close to each other so that each building form becomes a detail in the group form as a whole. In this case, the group form becomes more important than the individual building form in influencing the drag forces experienced by each building.

PRESENT INVESTIGATION

In the discussion so far, the problem of making a reliable estimate of the value of the wind pressure forces for natural ventilation calculations is shown to depend on two main groups of factors: form-related factors and flow-related factors. Thus, in urban areas where buildings are mostly in groups, it is expected that the three main factors affecting Δp are (1) the building geometry, (2) the group form and (3) the properties of the natural wind.

If the properties of the wind structure in the atmospheric boundary layer flow over suburban terrain are assumed to be known on the basis of previous full scale measurements, and if these properties can be adequately modeled in a wind tunnel, it should then be possible to conduct a series of detailed measurements to establish the existence of a set of relationships between the wind-induced pressure forces on a builidng and its immediate surroundings. It is the intent of this paper to demonstrate that such a set of relationships may be determined.

EXPERIMENTAL PROCEDURE

The series of experimental tests, to be described here, were conducted in the Sheffield University 1.2 × 1.2 m boundary layer wind tunnel. The wind tunnel has a working section 7.2 m long whose cross section measures 1.2 × 1.2 m, incorporating a 1.1 m diameter turntable and whose center lies 5.4 m downstream of the entry position.

The method used for the simulation of the suburban terrain atmospheric boundary layer utilizes an approach based on a combination of fences, spires, and floor roughness elements. The use of this method has been shown to give an adequate representation of both the mean velocity and turbulence characteristics appropriate to flow over suburban terrain conditions, Lee (1978).

Throughout the test program pressures were measured on a range of instrumented model buildings fitted with wall pressure tappings which were positioned at the center of arrays of identical models.

The overall investigation was conducted in three phases as follows

Phase 1
Cuboid models
Dimensions: 20mm cubes and 36mm cubes, H

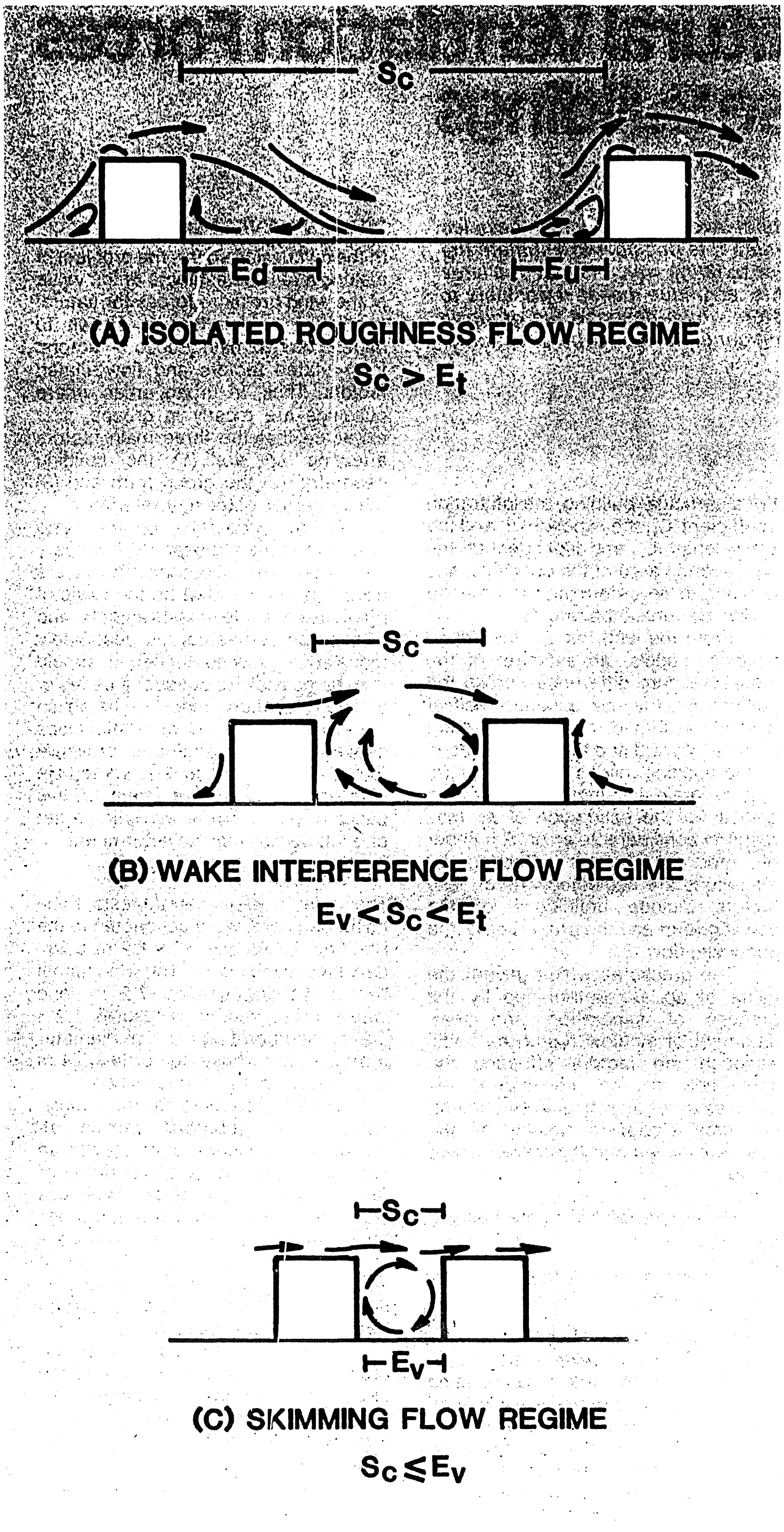

Fig. 1 Governing Conditions for the Three Flow Regimes

Array patterns: Normal (gridiron)
Staggered (checkerboard)
Random
Array plan area density: 3.1% to 50% (13 values)
Wind directions: $0° < \theta < 90°$

Phase 2

Frontal Aspect Ratio models, A_f
Dimensions: Front face 36mm × 1_1, side face 36 × 36mm where 1_1 = 18, 36, 54, 72 and 144mm
Array pattern: Normal (gridiron)
Array plan area density: 2.5% to 60% (15 values)
Wind direction: $\theta = 0°$, wind normal to front face

Phase 3

Side Aspect Ratio models, A_s
Dimensions: Side face 36mm × 1_2, front face 36 × 36mm where 1_2 = 18, 36, 54, and 72mm
Array pattern: Normal (gridiron)
Array plan area density: 2.5% to 60% (15 values)
Wind Direction: $\theta = 0°$ wind normal to front face.

In the tests included in phase 1 of the investigation, a study was made of the influence of the size of the array and the influence of upstream fetch. The results were then applied to phases 2 and 3. The results are presented in the form of pressure coefficients, normalized by means of a free stream or gradient wind velocity.

INFLUENCE ON SURFACE PRESSURES

When turbulent flow occurs over a rough surface composed of discrete roughness elements, it is possible to describe the existence of a number of flow regimes which are governed by the way in which the layout of elements occurs. These flow regimes, suggested by Morris (1955), and whose existence for some types of three-dimensional roughness element has been confirmed by Lee and Soliman (1977), are denoted as isolated roughness flow, wake interference flow, and skimming flow.

In the isolated roughness flow regime, Fig. 1a, the roughness elements are sufficiently far apart that each element acts in isolation, and behind which the wake and separation bubble develop completely, flow reattachment to the surface occurs before the next element is reached. Here the clear spacing in the flow direction between adjacent elements, Sc, is greater than E_t, the sum of the upstream separation distance, Eu, and the downstream distance, Ed.

In the third category, the skimming flow regime, Fig. 1c, the roughness elements are not sufficiently close together that a stable vortex can form in the space between the elements and the flow appears to skim on their crests. Here the separation distance between elements is less than E_v, the maximum gap size for the existence of such a stable vortex.

The wake interference regime, Fig. 3b, then exists between these other regimes where the separation bubble does not have sufficient space to develop fully, but where the distance is too large for a stable vortex to remain. Here the clear spacing lies between E_t and E_v.

CUBOID MODEL TESTS

The measurements of the mean surface pressure forces were first carried out on the cuboid models. Fig. 2, which presents these results, shows the variation of ΔC_{p_1} with element clear spacing ratio S_c/H, and plan area density λp, for both the normal and staggered patterns, where ΔC_{p_1} is the coefficient of Δp as defined in section 3.

These results are shown to be represented by broken straight line relationships for both layout patterns considered, where break points are considered to reflect a change from one flow regime to the next.

"... Building design must be accomplished within both economic and environmental constraints ..."

From this figure the following conclusions are suggested

(1) The isolated roughness flow regime exists for values of $S_c/H > 2.6$ for both layout patterns.

(2) The wake interference flow regime exists for values of $1.4 < S_c/H < 2.6$.

(3) The skimming flow regime exists for values of $S_c/H < 1.4$ for both layout patterns.

Fig. 4 also shows the value of ΔC_{p_1} for an isolated cuboid model building in the simulated atmospheric flow. A comparison of this value with those for the pressure drop across grouped buildings clearly illustrates the importance of building proximity effects in determining wind pressure forces and wind-induced ventilation rates.

FRONTAL ASPECT RATIO VARIATION

The variation of the central model pressure drop coefficient, ΔC_{p_1}, with variations in array model clear spacing for the range of frontal aspect ratio models from $A_t = 0.5$ to $A_t = 4.0$, were studied in phase 2 of the investigation

The inflection points in the relationship between the model pressure drop and the clear spacing ratio were similar to those found for the cuboid models. But, this leads one to conclude that the values of S_c/H at which the flow regime changes occur depend not only on the model spacing, but also on the value of the model's frontal aspect ratio.

Across the range of frontal aspect ratio from 0.5 to 4.0 it was found that the change of flow regime from isolated roughness flow to wake interference flow occurs at values of S_c/H which progress from 2.25 to 3.0 respectively. Similarly, the values of S_c/H at which the second change occurs also increase from 1.30 to 1.55 across the same range of frontal aspect ratio models.

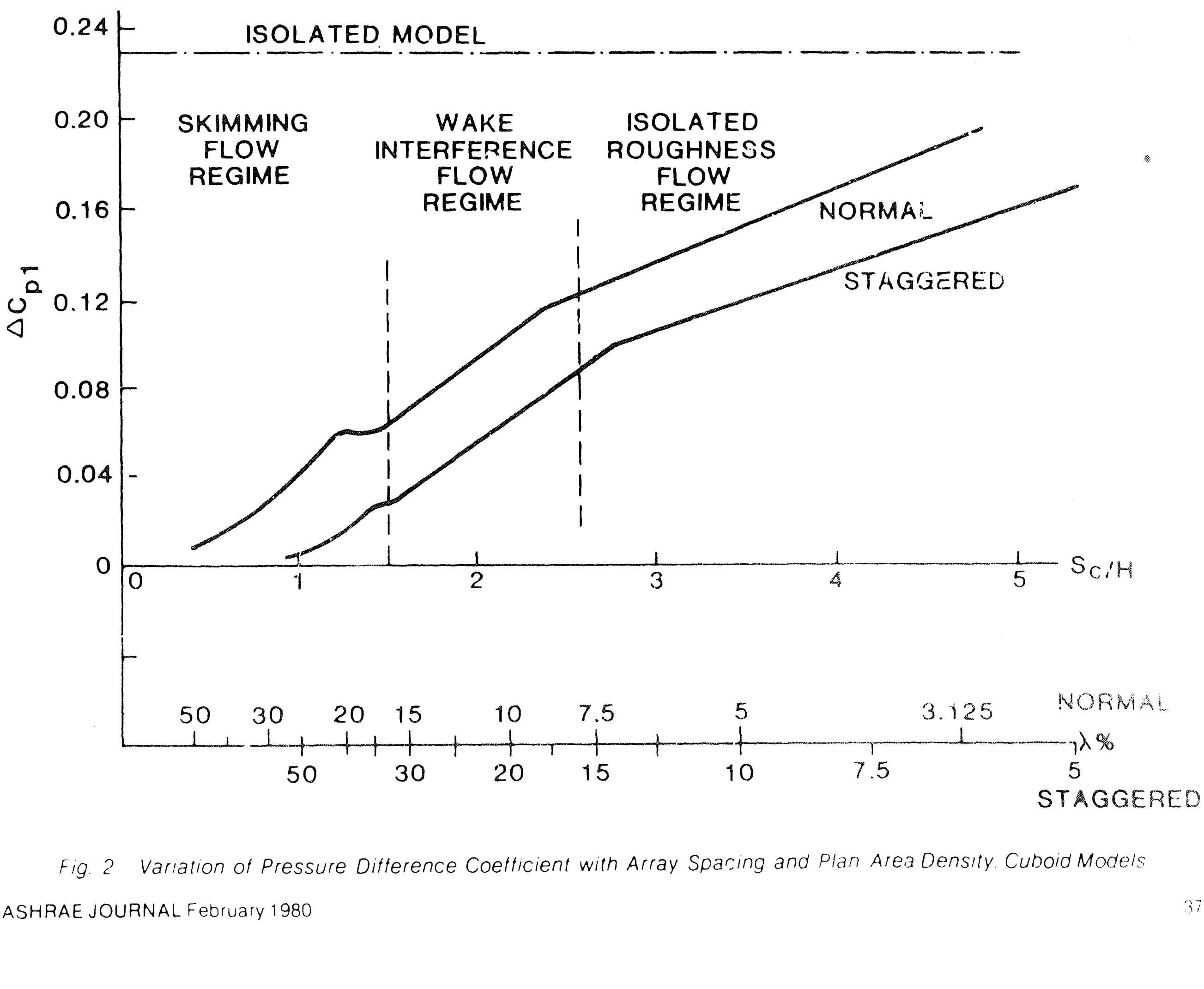

Fig. 2 Variation of Pressure Difference Coefficient with Array Spacing and Plan Area Density. Cuboid Models

". . . A proper estimate of the natural ventilation rates is necessary if buildings are to meet environmental and economic requirements . . ."

SIDE ASPECT RATIO VARIATION

Phase 3 of the investigation then examined the variation of the model pressure drop coefficient, ΔC_{p_1}, with the model clear spacing, S_c, for values of the side aspect ratio models of $A_s = 0.5$, 1.0, 1.5, and 2.0. The inflection points in the rate of reduction of model pressure drop with spacing were again used to identify the changes in flow regimes.

The first change from the isolated roughness to wake interference flow regimes occurred at values of S_c/H varying from 2.1 to 2.6 as the side aspect ratio was increased from 0.5 to 2.0. The second change from the wake interference to the skimming flow regime occurred at a constant value of S_c/H of 1.4 for all model side aspect ratio array values.

FETCH LENGTH CORRECTION

The influence of upstream fetch on the surface pressures acting on the central model, for arrays of cubes, was studied in phase 1 of the investigation. The model group fetch size required for the surface pressures to stabilize at their minimum value varied from 10H to 25H and was dependent also on the group plan area density for groups of buildings situated within a suburban terrain atmospheric boundary layer

From these tests, it was found that if the fetch length was too short for the conditions of pressure stabilization to occur, then, this would result in an increase in the surface pressure forces. It was possible then, using the results of all the tests on the influence of upstream fetch length, to produce a family of curves for each of the flow regimes indicating the increase in surface pressure difference which is consequent upon the existence of short fetch lengths.

INFLUENCE OF WIND DIRECTION

The data on the influence of wind direction on the surface pressures acting on groups of low-rise buildings stem from a series of tests on groups of cuboid models in normal, staggered, and random layout patterns.

The variation of ΔC_{p_1} with the model orientation, θ, is shown in Fig. 3, where the values for all layout patterns were averaged for three values of the

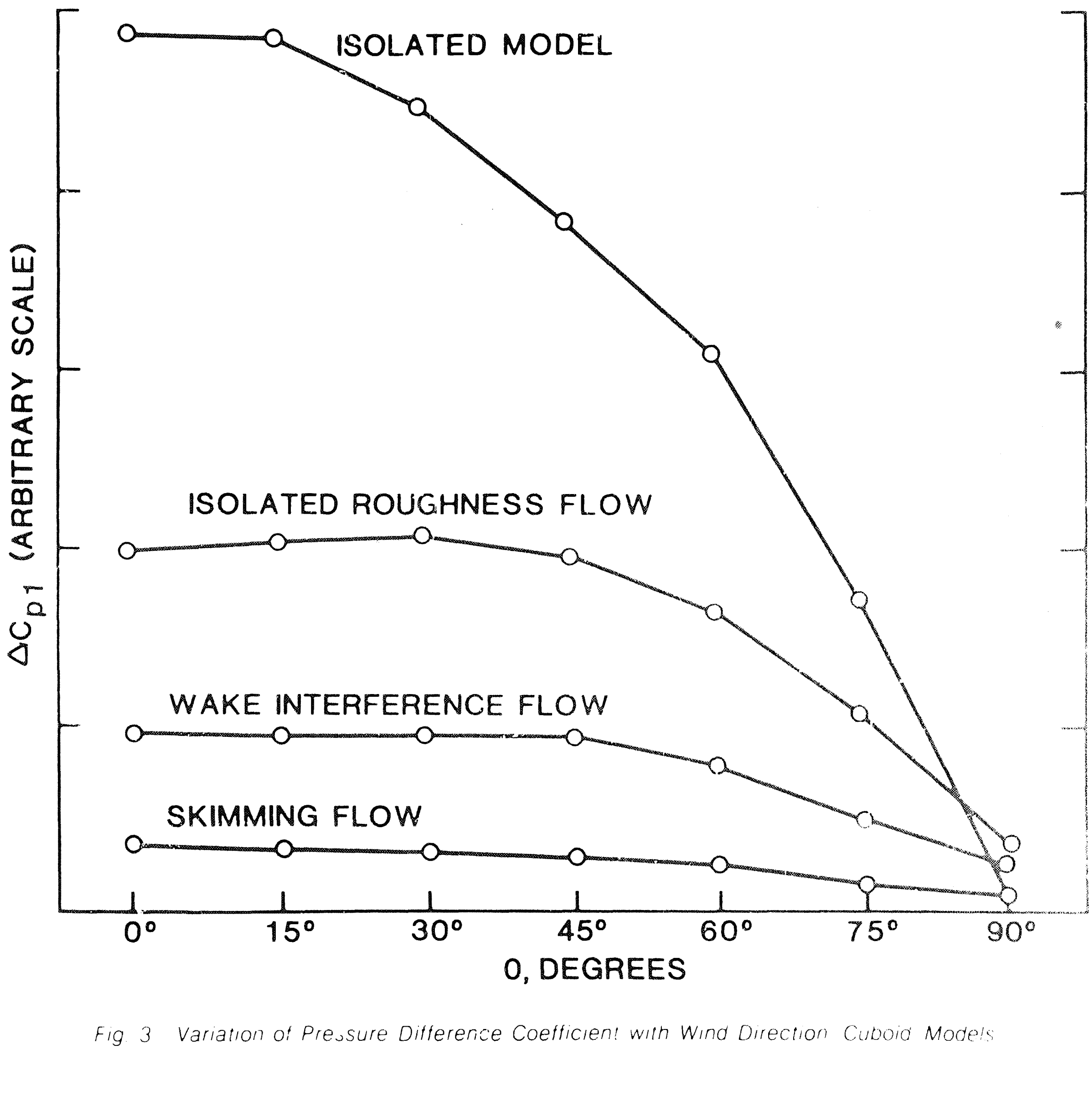

Fig. 3 Variation of Pressure Difference Coefficient with Wind Direction Cuboid Models

Example 1 $A_f = 1.5$, $A_s = 1.0$, $S_c/H = 3.0$, $R/H > 25$, $\theta = 60°$ $\Delta C_{p_1} = 0.104$

Example 2 $A_f = 1.0$, $A_s = 0.5$, $S_c/H = 3.5$, $R/H = 15$, $\theta = 0°$ $\Delta C_{p_1} = 0.228$

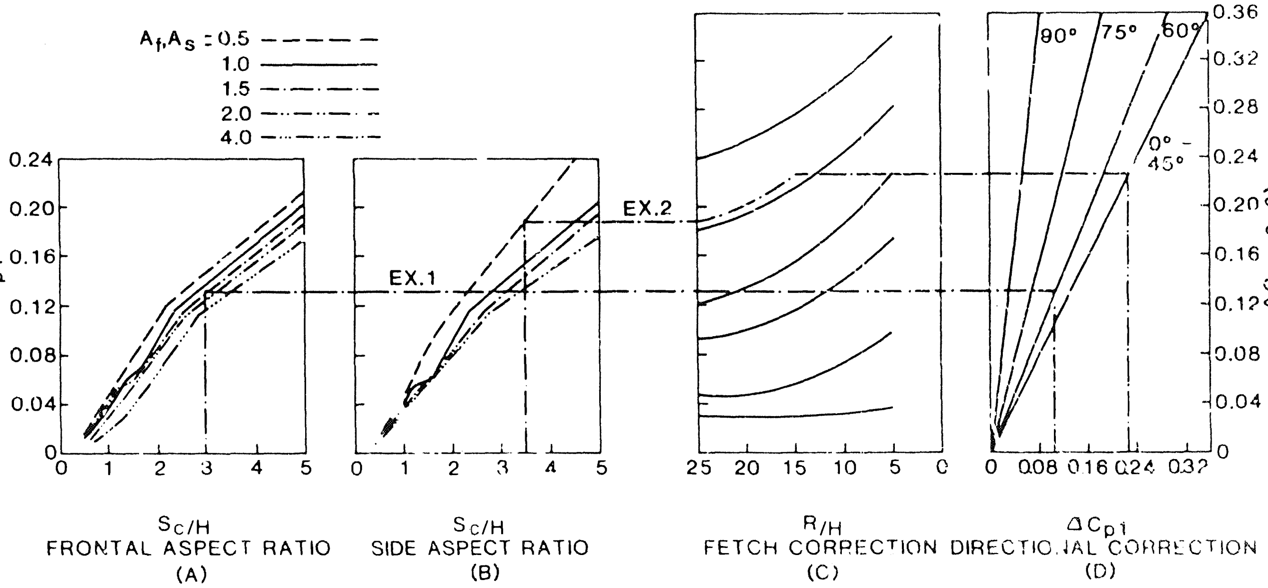

Fig. 4 Graphical Prediction Technique for Pressure Difference Coefficients

group plan area density corresponding to the three flow regimes. A comparison with the corresponding data for an isolated cuboid model is also presented.

The effect of model orientation on the value of ΔC_{p_1} in the range of $0° < \theta < 45°$ is shown to be negligible for the values of density considered.

PREDICTION METHOD

Having seen the effect of the important parameters which influence the value of the side wall pressure difference coefficient, ΔC_{p_1}, a prediction procedure for low-rise buildings is now possible. Assuming the buildings to be of similar heights in a group, a chart can be constructed by placing the parametric data sets side by side, as shown in Fig. 4. Parts a and b of Fig. 4 indicate the variation of ΔC_{p_1} for models of various frontal or side aspect ratio, determined in a similar manner to that for the cuboid model data shown in Fig. 2. Part c of Fig. 4 is the upstream fetch length correction, which enables an increased value of ΔC_{p_1} to be used for short upstream array distances. Part d of Fig. 4 enables a correction to be made which allows for the reduced values of ΔC_{p_1}, which occur when the wind is not normal to the front face, and has been derived from Fig. 3. Two examples showing the sequence of these steps are indicated, for different frontal and side aspect ratio buildings. Since ΔC_{p_1} is defined as

"... It is surprising that so little is known about air infiltration in low-rise buildings ..."

$$\Delta C_{p_1} = \frac{\Delta p}{1/2 \rho V_G^2}$$

it requires only a knowledge of V_G, the gradient wind speed, in order to determine Δp. A significant advantage of this procedure is that it is not necessary to involve an estimate of the wind velocity at the building roof height: an especially difficult procedure where the average roof height of an array of low rise buildings is below the standard meteorological reference height. However, this independence of the roof height velocity is an assumption which is only valid if the ratio of building height to boundary layer thickness is small.

A more complete explanation of this prediction method is available by Lee, Hussain and Soliman (1979).

CONCLUSIONS

A prediction technique has been presented which enables the surface pressures acting on a particular building, situated within an array of similar low rise buildings, to be estimated. The procedure takes account of both the geometrical form of the building and the spacing parameters which describe the array as well as the direction of the wind and the upstream fetch conditions. The estimated value is in the form of a pressure coefficient, non-dimensionalized with respect to a gradient wind speed, and may be determined by means of a graphical method.

REFERENCES

ASHRAE Inc. Handbook of Fundamentals, New York City, NY (1972)

Lee, B.E. The Simulation of Atmospheric Boundary Layers in the Sheffield University 1.2 × 1.2m Boundary Layer Wind Tunnel. Proc. 3rd Coll. Ind. Aero., Fachhochschule Aachen, F.D.R., (June 1978)

Lee, B.E. and Soliman, B.F., An Investigation of the Forces on Three Dimensional Bluff Bodies in Rough Wall Turbulent Boundary Layers. Trans. A.S.M.E. Jnl. Fl. Engng. Vol 99, (September 1977)

Lee, B.E., Hussain, M. and Soliman, B.F. A Method for the Assessment of the Wind Induced Natural Ventilation Forces Acting on Low Rise Building Arrays. Univ. of Sheffield Dept. Build. Sci. Rep. No. BS[illegible] (March 1979)

Morris, H.M., Flow in Rough Conduits, Proc. A.S.C.E. Vol. 120 Paper [illegible] ([illegible])