SINGLE-SIDED VENTILATION THROUGH OPEN WINDOWS

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ABSTRACT

Natural ventilation provided by open windows is an essential contributory factor in controlling summer temperatures in non-air conditioned buildings. Where this is provided by cross-ventilation the underlying mechanisms are well understood. However, there are many circumstances in which cross-ventilation is restricted, for instance when the ventilated space is relatively well-sealed from the remainder of the building. Typical examples are cellular offices or school classrooms in which internal doors to central corridors are kept closed for reasons of privacy or noise and in which openable windows are situated in one external wall.

In such spaces ventilation is achieved by the exchange of air through the windows on one side of the space rather than by cross-ventilation. This paper discusses the mechanisms available for 'single-sided' ventilation and describes a simple approach to its prediction, based upon a combination of theoretical modelling, wind tunnel studies and tracer gas measurements in full scale buildings. Further wind tunnel and tracer gas measurements are also described which show the effect of degree of opening, window type and combination of windows on the magnitude of the ventilation rate.

INTRODUCTION

The primary mechanism for the transfer of air across the building envelope is the generation of a pressure difference across adventitious or purpose built openings, either by the wind or by stack effect. The general principles of cross ventilation have been understood for many years and have been incorporated in a number of prediction procedures. There are, however, situations when cross ventilation is restricted, for instance when a ventilated space is well sealed from the remainder of the building. Typical examples include school classrooms or cellular offices with internal doors which are generally kept closed for reasons of privacy and which have openable windows on one external wall only. In such spaces ventilation is achieved by the exchange of air through open windows on one side only. For present purposes this will be referred to as 'single-sided' ventilation.

This paper reviews the mechanisms available for single-sided ventilation and proposes some simple guidance for the designer based upon theoretical considerations, wind tunnel studies and full scale tracer gas measurements in two buildings.

MECHANISMS OF SINGLE-SIDED VENTILATION

As with cross ventilation, the two main agencies that can give rise to single-sided ventilation are (1) stack effect, generated by temperature differences across the building envelope,

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of mean pressure at the surface will give rise to a different, Δp, between, say, two openings. Expressing this in terms of a differential, ΔC_p, in pressure coefficient, based upon U_T, leads to the following simple expression for F_T:

$$F_T = (0.35).C_d.\Delta C_p^{0.5} \tag{8}$$

C_p will depend upon the rate of change of velocity across the surface of the building and the distance between the openings. In general the latter will be small in comparison with the overall dimensions of the building. For most buildings ΔC_p is not likely to exceed 0.1. Substitution into Equation 8 gives a value for F_T of approximately 0.07. From general consideration of the nature of airflow around a building this yields a local flow number, F_L, of approximately 0.1.

Turbulent Diffusion. The airflow past an opening will be highly turbulent, and the turbulence will generate mixing across the opening enabling air to be exchanged between the room and the outside air. The complexity of the flow makes analysis difficult. However, since the dimensions of a typical window are likely to be small in comparison with those of the building itself, it is reasonable to assume that the flow in the vicinity of an opening or window will be parallel to the surface of the building. Neglecting turbulence and the effects of three-dimensionality of the opening, a simple representation of the flow at the opening is the classical mixing layer formed when a uniform stream is exposed to a region of zero velocity at one edge. Although highly idealized, this type of flow is well understood and provides an initial basis for estimating the turbulent interchange of fluid across the opening.

Figure 2 shows the assumed flow pattern. At the outer edge of the mixing layer, the velocity is taken as U_L, while at the inner edge, the longitudinal velocity is zero. At Reynolds numbers consistent with typical magnitudes of U_L and opening dimensions, the flow will be turbulent and air will be entrained at the inner edge and will mix within the layer. The layer is of finite length, equal to that of the opening. When it intersects with the downstream edge of the opening, part of the layer will be deflected back into the space and part will continue downstream with the general airflow. The latter will contain air previously within the space. This provides a mechanism for air exchange between the space and outside air.

This forms the basis for a mathematical model, set out and discussed by Warren (1978). Using suitably chosen profiles for the distribution of velocity and concentration of species within the mixing layer taken from Abramovitch (1963), the following expression was derived for the dimensionless flow:

$$F_L = 0.056 \quad \alpha \tag{9}$$

α is a measure of the rate at which the mixing layer spreads. Abramovitch (1963) quotes values in the range 0.2 to 0.3 and notes that α will be increased by turbulence in the free stream. Liepmann and Laufer (1947) determined an experimental value of 0.23, using a virtually turbulence-free freestream. Substituting this value into Equation 9 gives a value for F_L of 0.013.

In practice, as noted earlier, the real flow at an opening will differ substantially from the idealized model proposed above, principally in the following respects:

1. The freestream will be highly turbulent, possessing a wide range of eddy sizes, and it is reasonable to expect that the layer would be considerably thickened and distorted, giving rise to values of substantially higher than that quoted by Liepmann and Laufer (1947) of 0.23.

2. The flow will be three- rather than two-dimensional, particularly if the local flow direction is not parallel to one of the main dimensions of a rectangular opening.

Both of these would tend to increase, rather than reduce, mixing. Consequently, the value for F_L of 0.013 may be treated as a minimum. Measured data covering conditions (1) and (2) above are sparse. Brown and Solvason (1962), in studies of heat transfer through rectangular openings in vertical, insulated partitions, report limited experiments to determine the effect of a flow parallel to the partition. The flow was produced by conventional air-conditioning fans, upstream of the opening, and would be expected to be highly turbulent, containing eddy sizes comparable to the dimensions of the openings used. For high velocities, the heat transfer across the opening was found to be independ of Grashof number, indicating that the exchange process was dominated by the airflow rather than the temperature difference. These results have been used to calculate values of F_L for two sizes of square opening used, as follows:

Dimensions of opening	F_L
9 in x 9 in	0.096
12 in x 12 in	0.090

The implied values of α for the two cases are 1.71 and 1.60 and clearly incorporate, not only the increase in mixing layer thickness, but the three-dimensional nature of the flow at the opening.

Single Opening with Vane. While the discussion in turbulent diffusion is relevant to openings limited to the plane of the building surface, such as sliding windows, many other openings, such as center-pivoted and casement windows, include a vane which protrudes into the local airflow. This adds additional complexity to the flow at the opening and which becomes even less amenable to theoretical analysis. For this reason the problem was approached by using controlled wind tunnel studies described later.

Combined Stack and Wind Effect. Thus far, stack and wind effect have been considered separately. In practice, in real buildings, they will act together. This introduces an additional dimensionless variable, the Archimedes number - Ar, into the determination of Flow Number, F. Archimedes number is defined as follows:

$$Ar = [\Delta\theta.g.z/\theta U^2] \tag{10}$$

Where z is an appropriate vertical dimension, such as the height of a single opening, h, or the vertical distance between two openings.

Thus for a particular opening on a particular building, F_R is given by:

$$F_R = f[Ar, \gamma] \tag{11}$$

When Ar is large, the flow rate will tend to that predicted for stack effect alone, for instance by Equation 4. This may be rewritten in the following form:

$$F_R = (C_d/3).J(\phi).(Ar)^{0.5} \tag{12}$$

When wind dominates, Ar tends to zero and F_R becomes independent of Ar. This suggests a useful basis for analyzing the results of full-scale measurements, where control over variables such as wind speed and direction and external temperature are not possible. If the results are plotted in the form F_R against $Ar^{0.5}$, measurements dominated by stack effect will lie close to a straight line passing through the origin, of a form similar to that defined by Equation 12 (chosen to be appropriate for the opening(s) under consideration). Those dominated by wind will deviate from this line and lie between it and the F_R axis.

WIND TUNNEL STUDIES

Experimental Arrangement

A small open-circuit wind tunnel with an enclosed working section of height, 2.6 ft (0.8 m) and width 3.6 ft (1.1 m) was modified by constructing a small test chamber in the side wall of the tunnel, as shown schematically in Figure 3. The chamber had a cross-section of 20 in x 20 in (0.5 m x 0.5 m) and a depth, away from the tunnel wall, also of 20 in (0.5 m). The wall common to the chamber and the tunnel working section was constructed to allow panels containing openings of various types to be inseted flush with the tunnel wall and sealed to prevent leakage. This arrangement allowed a uniform airflow to be induced parallel to the plane containing an opening, with a velocity in the range 3.5 ft/s (1.1 m/s) to 17.0 ft/s (5.2 m/s).

The exchange of air across the opening was measured using a constant injection rate tracer-gas technique. Nitrous oxide was introduced into the chamber at a known constant rate through an array of uniformly distributed injection points and sampled using a similar array. The equilibrium concentration of the tracer gas was measured using an infrared gas analyzer and used to calculate the ventilation flow rate, Q. For any given opening, measurements were made for five to six values of tunnel speed. In practice, with all of the openings for which results are given in this paper, measured ventilation rates increased linearly with air speed, allowing for experimental error. This implies that the function f[ ] in Equation 6 is constant and that the flow is therefore independent of Reynolds number.

Plane Openings

In order to extend the data available on plane openings, measurements were made with two types:

- square openings, and
- slot openings with the longest dimension perpendicular to the direction of flow and equal to the height of the chamber.

It was not possible to induce turbulence in the freestream of a sufficient magnitude to fully represent the full-scale situation. However, in addition to the normal uniform flow, a second condition was set up in which turbulence was increased by installing a wooden grid across the working section, 5.0 ft (1.52 m) upstream of the center of the opening in the chamber wall. The grid was bi-planar, consisting of 1.80 in x 0.28 in (46 mm x 7 mm) slats, with the longer dimension set perpendicular to the flow, arranged in a square pattern at 5.83 in (148 mm) centers. The grid was sized to give a lateral scale of turbulence $L_y(u)$ at the opening of 1.0 in (25 mm). The intensity of the longitudinal component of turbulence was measured and found to be 9.0% in comparison with the level of 0.8% in the unmodified flow.

Figure 4 shows a typical set of results, in this case for a square opening, of side 12.0 in (0.25 m). Two sets of results are shown for the normal tunnel operating condition, without the grid. These were made at different times, with slightly different tracer-gas arrangements. There is no significant difference between the two sets, indicating an encouraging degree of repeatability. Taken together the results yield a value for F_L of 0.023, somewhat higher than the theoretical minimum value, calculated from the two-dimensional mixing layer model discussed above, of 0.013. The presence of enhanced turbulence, created by the grid, increases the air exchange rate, giving a value for F_L of 0.034.

The results for the range of openings tested are summarized in Table 1. Several general points may be noted:

1. The values of F_L are significantly higher for the square than the slot opening. In the latter case the flow is much closer to the idealised two-dimensional case, and the results give some support to the contention, made above, that three-dimensional effects are likely to enhance mixing.

2. For both types of opening, the presence of enhanced turbulence in the freestream flow increases the value of F_L, on average by 60% for the slots and by 40% for the square openings. Again this disparity reflects the higher contribution due to three-dimensional effects in the latter case.

Single Opening with Vane

The effect of an opening vane was studied by inserting models of openable casement windows in the test chamber wall. Three model windows were used, each of area 40 in^2 (0.026 m^2), but with different aspect (height to width) ratios of 1.0, 1.6 and 2.5. Measurements of air exchange rate were made in each case for four angles of opening, ϕ: 10, 30, 60, and 90° and three directions of flow relative to the window, β: 0, 90, and 180°. The sense of ϕ and β is indicated in Figure 5. For each arrangement measurements were made for five or six values of tunnel velocity, in the range 3.5 ft/s (1.1 m/s) to 17 ft/s (5.2 m/s).

The measured ventilation rates were found to vary linearly with flow speed, again, as with the plane openings, indicating an absence of Reynolds number effects and giving confidence in applying the results to the full scale. The results are shown in Figure 5. Substantially higher values of F_L are found for $\beta = 0$ than for the two other directions. A possible explanation is that for this condition the exchange is almost entirely due to the complex, three-dimensional flow created by the presence of the vane; whereas for the other flow directions, turbulent mixing processes, similar to those discussed previously for plane openings, also contribute. In support of this, it may be noted that the results for the condition, $\beta = 90°$

and ϕ = 90°, yield values of F_L of approximately 0.025, close to the values obtained for plane square openings.

It is of interest to note that the angle of opening, ϕ, has relatively little effect for ϕ much greater than approximately 50° but is a relatively sensitive means of control when ϕ is less than approximately 30°.

Two Openings with Vanes

Additional studies, using model side-mounted casement windows, were undertaken to investigate the effect of two such openings. The windows were identical, each with aspect ratio 1.25 and area 20 in^2 (0.013 m^2). Measurements were restricted to flows parallel with the line of the windows. Four configurations were studied, and for each the distance separating the windows was varied from 0.5 to 2.5 times the window width of 4 in (0.0102 m).

The results and the configurations investigated are shown in Figure 6. Direct comparison with the results for single windows is difficult in the case of the symmetrical arrangements (a) and (b) because of the difficulty of choosing an appropriate value of β. However this is not the case for (c) and (d), which correspond to β = 0° and 180° respectively. The aspect ratio of 1.25 lies between the values of 1.0 and 1.6 used in the single-window experiments. However, there is relatively little difference between these and either may be taken for present purposes. For angles of opening of 10 and 30°, the results for (c) are lower than for a single opening and noticeable improvement only occurs at opening angle of 60° with the spacing greater than one window width. The same is also true of arrangement (d) where comparison may be made with the single window for β = 180°. Taking into account the fact that the wind direction may be equally likely to be at β = 0 or 180°, the most advantageous arrangement is (a), which provides an overall benefit over a single window of between 50% and 100%, depending upon spacing, for an angle of opening of 60°.

FULL-SCALE MEASUREMENTS

Although the analysis and wind tunnel studies described in the preceding sections give a useful insight into the possible mechanisms and magnitude of single-sided ventilation, they cannot fully represent the conditions that apply in the full-scale situation. For this reason measurements were made in rooms in two buildings.

In the first the intention was to provide data for comparison with the theoretical and wind tunnel studies. The second was used to obtain data on the general effect of having more than one window open in a room.

Building 1

Experimental Arrangement. The measurements were made in two rooms, A and B, of a single-storey building. Figure 7 shows a general view of the building and Figure 8 shows the position of the rooms in plan and the window arrangement. Room A was fitted with a pair of vertically sliding windows and room B with two side-mounted casement windows. The internal surfaces of the rooms were sealed to eliminate cross-ventilation.

Ventilation rates were measured by conventional tracer gas decay rate technique using nitrous oxide and a Maihak infra-red gas analyzer. Over the period of each ventilation rate measurement the wind speed, U_R, and wind direction, γ, were measured locally at a height of 32.8 ft (10 m) and the internal and external were recorded. The estimated accuracies of measurement were 10% for ventilation rate, 1.5 ft/s (0.5 m/s) for wind speed and 0.4°F (0.25°C) for temperature.

Results.

(1) Vertically sliding windows - Room A.

Two conditions were investigated:

(a) a single opening of height 6 in (0.15 m) and width 3.28 ft (1.0 m), and

(b) two openings, each of height 3 in (0.75 m), and width 3.28 ft (1.0 m) separated vertical by a height of 3.80 ft (1.16 m).

Measurements were made for a wide range of U_R, γ, and $\Delta\theta$. Using the approach set out above the results have been plotted, for each condition, in Figures 9a and 9b, in the form F_R against Ar_R. Also shown are the theoretical lines for buoyancy dominated flow in each case. As might be expected, rather more of the measurements are dominated by buoyancy in the case of arrangement (b). By observation those results dominated by wind were isolated and also shown in Figures 9a and 9b, plotted against wind direction, γ.

(2) Side-mounted casement windows - Room B.

Measurements were made for a single window, opened to six positions, determined by the design of the stay. These were equivalent to the following values of ϕ - 4, 12, 20, 27, 34 and 67°. Using the same method as for the sliding windows the wind dominated results were isolated and are plotted in Figure 10 against wind direction.

Discussion of Results. The results are useful in themselves as broad indicators of the magnitude of single-sided ventilation due to wind effect for the particular building and window arrangements concerned. However, in order to generalize the results and to use them for comparison with the preceding theoretical analysis and wind tunnel studies, they need to be expressed in terms of local airspeed, U_L, rather than reference wind speed, U_R. In order to do this, an expression of the form of Equation 5 is required. For a particular location on a particular building, this means expressing (U_L/U_R) and β as functions of wind direction, γ.

In order to do this, a 1/25 scale model of Building 1 was constructed and set up in the wind tunnel on a turn-table in the center of the working section. A simple grade rod array was used to give a 1/7 power law wind profile, appropriate to the location of the full-scale building. No attempt was made to simulate atmospheric turbulence. The local airspeed at the position of the sliding windows was measured using a hot wire anemometer aligned in the direction of flow, β, in a plane parallel to the surface, determined by a wool tuft. The reference wind speed, U_R, was measured at the equivalent scaled height in the upstream flow.

The results for the ratio (U_L/U_R) are shown as a function of wind direction, γ, in Figure 7. These have been used to transform the results for each of the sliding window arrangements. The results are shown below:

Window arrangement	Number of results	Flow number mean	Flow number S.D
Single opening	23	0.105	0.030
Double opening	10	0.115	0.025

The difference between the means is not statistically significant. The large spread in the results is not unexpected, taking into account the errors in the full-scale measurements of Q and U_R as well as in the wind tunnel measurement of (U_L/U_R). The mean values are much higher than the theoretical value for a non turbulent freestream, of 0.013, and higher than the wind tunnel chamber studies. However the results are comparable with those of Brown and Solvason (1962) and can be accounted for by the much higher levels and scales of turbulence likely to be found at full-scale and the three-dimensional nature of the flow.

The results for the side-mounted casement window, room B, can be similarly transformed. However, in this case the wind tunnel studies indicate that it is important to take into account the local wind direction, β. Direct comparison with the wind tunnel studies is limited to the three values for β of 0, 90 and 180°. The results using the scale model of Building 1 showed that these were found in the following ranges of, wind direction, γ:

1. $20<\gamma<70$: $\beta = 0°$
2. $150<\gamma<210$: $\beta = 90°$
3. $290<\gamma<340$: $\beta = 180°$

The full-scale results were limited to the wind directions that obtained at the time at which the measurements were and are, therefore, not conveniently distributed, the majority lying within range (1), corresponding to $\beta = 0$. The calculated values of F_L have been averaged for each of the six values of window opening angle, ϕ, and are plotted in Figure 11. For comparison the results from the wind tunnel studies for the side-mounted casement window of aspect ratio, M = 1.6, given in Figure 5, have also been included. The agreement is surprisingly good. Unfortunately the sparsity of results in the other ranges, does not allow an equivalent comparison for the other values of β. There are a limited number of results in range 3, i.e., for β = 180°. The average value of F_L for these is 0.07, substantially higher than the wind tunnel result of 0.03. A possible reason for this is the influence of the high level of turbulence present in the full-scale situation.

Building 2

Experimental Arrangement. The measurements were made in two classrooms situated in the main building of a large secondary school. The rooms were situated on the second floor and their positions are shown in the elevation of the building shown in Figure 12. Each room was identical in size (height - 2.7 m; depth - 6.7 m; width - 9.8 m) and had one external wall. Access to each was via a central spinal corridor. For experimental purposes, room A was fitted with vertical sliding windows and room B with a combination of side-mounted casement windows. The arrangement of these windows and the combination of openings used in the present studies are shown in Figures 13a and 13b respectively. The overall size of each sliding window was 40 in x 15 in (1.02 m x 0.38 m), which allowed a maximum open area of 4.2 ft^2 (0.39 m^2). The overall size of the casement windows was 26 in x 42 in (0.66 m x 1.06 m) allowing a maximum open area of 7.6 ft^2 (0.70 m^2). For these studies, only one value of angle of opening of the casement windows was used - 65°.

Measurements of ventilation rate were made using the same technique and equipment as for Building 1. Internal and external air temperatures were similarly measured. It was not possible to measure wind speed and direction in the immediate locality of the building, and these were obtained from the nearest meteorological site, approximately 5 miles east of the site.

Results. The results were analyzed using the same method as outlined for Building 1. They were initially plotted in the form - F_R against Ar_R and then inspected to identify those results dominated by wind effect. These were plotted against wind direction (measured relative to the perpendicular to the facade containing the windows) for each of the opening arrangements chosen and are shown in Figures 14a and 14b for rooms A and B respectively.

Discussion. For both types of window, the minimum value of F_R is approximately 0.03, with much higher values occurring when the wind is directed at the facade containing the windows, i.e., for wind directions approximately in the range 300° to 060°. These results are consistent with the previously suggested value of 0.1 for F_L if (U_L/U_R) were to vary in a similar way to that for Building 1, allowing for the different heights of the buildings and the variation of wind speed with height. This is a reasonably plausible assumption since the highest surface wind speeds may be expected on the windward face of a building where the flow is accelerated. Leeward faces would tend to be in regions of separated flow where the surface speeds would be lower.

One particular arrangement of side-mounted casement windows, with the openings facing in opposing directions, gives substantially higher values of F_R in the range of wind direction 300 to 060 than the other arrangements. This is consistent with the results of the wind tunnel studies shown in Figure 6.

There is some evidence from Figure 14a that the values of F_R for the sliding windows are higher when the distance separating the windows is larger. This would be consistent with influence of the mean pressure different mechanism discussed earlier. ΔC_p is likely to be higher as the distance between openings is increased.

CONCLUSION

Possible mechanisms for the ventilation of spaces that have open windows on one side only have been discussed and wind tunnel and full-scale measurements have been presented. Single-sided ventilation is a more complex process than cross-ventilation, but it is possible to draw a number of conclusions.

1. The main mechanisms that may give rise to single-sided ventilation are:

   (a) stack effect,

   (b) turbulent diffusion, and

(c) aerodynamic interaction with window opening light.

In addition, where there is more than one opening to a space, the following mechanism may also be important,

(d) mean pressure difference.

These each give ventilation rates of broadly the same order of magnitude and are substantially larger than other possible mechanisms, such as turbulent pressure fluctuation and molecular diffusion.

2. For mechanisms (b) and (c), due to wind, a relatively simple relationship has been established, which enables flow rate, Q, to be calculated from the area of the opening, A, and the local air speed, U_L, generated at the surface of the building in the vicinity of the window:

$$Q = (0.1).A.U_L \tag{13}$$

Existing results for relatively low-rise buildings indicate that the ratio of U_L to a suitable reference wind speed, U_R, measured at a standard height, is unlikely to fall below 0.25. This value yields the following relationship, which may be used as a guide to designers when estimating single-sided ventilation through open windows:

$$Q = (0.025).A.U_R \tag{14}$$

3. The effect of angle of opening for windows such a side-mounted casement has been examined, both for stack and wind effect. The opening light provides a reasonably fine control for angles of opening up to approximately 30° but, thereafter, becomes progressively less effective and, beyond an angle of about 50°, the ventilation rate is close to that with the window fully open.

4. Equation 14 represents a minimum estimate of ventilation rate. In practice higher rates may be achieved with the same area of opening for:

-- combination of windows

-- certain wind directions

-- tall buildings.

5. Further research is required to investigate the interaction of mechanisms (a) to (d) above and to establish more data on air speeds at the surfaces of buildings of different built form and surroundings.

6. To indicate the magnitude of single-sided ventilation rates, typical values may be substituted in the formulae given here for stack and wind effect. For a room of height 8 ft (2.4 m) and with openable window area equal to 1/20th of the floor area, Equation 14 yield a ventilation rate of approximately <u>8 ach</u> at a wind speed of 10 mph (4.4 m/s). For a single window of height 3 ft and the same area, the ventilation rate for a typical summer-time temperature difference of 5 F (2.8°C) is approximately <u>4 ach</u>.

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ACKNOWLEDGMENTS

This paper was contributed by courtesy of the Director, Building Research Establishment, United Kingdom, and is reproduced by permission of the Controller, HMSO.

TABLE 1
The effect of a Turbulence-Producing Grid on Flow Number F_L for Square and Slot Openings

Opening Type and Size	Flow Number - F_L	
	No Grid	Grid
SQUARE		
5.0 x 5.0 in	0.025	0.035
7.0 x 7.0 in	0.026	0.035
10.0 x 10.0 in	0.023	0.034
SLOT		
1.0 x 20.0 in	0.014	0.023
2.0 x 20.0 in	0.019	0.029
4.0 x 20.0 in	0.017	0.029
7.0 x 20.0 in	0.015	0.022
10.0 x 20.0 in	0.014	0.022
Free stream turbulence:		
u/U_L	0.8% (meas)	9.0% (meas)
$L_y(u)$	-	1.0 in (calc)

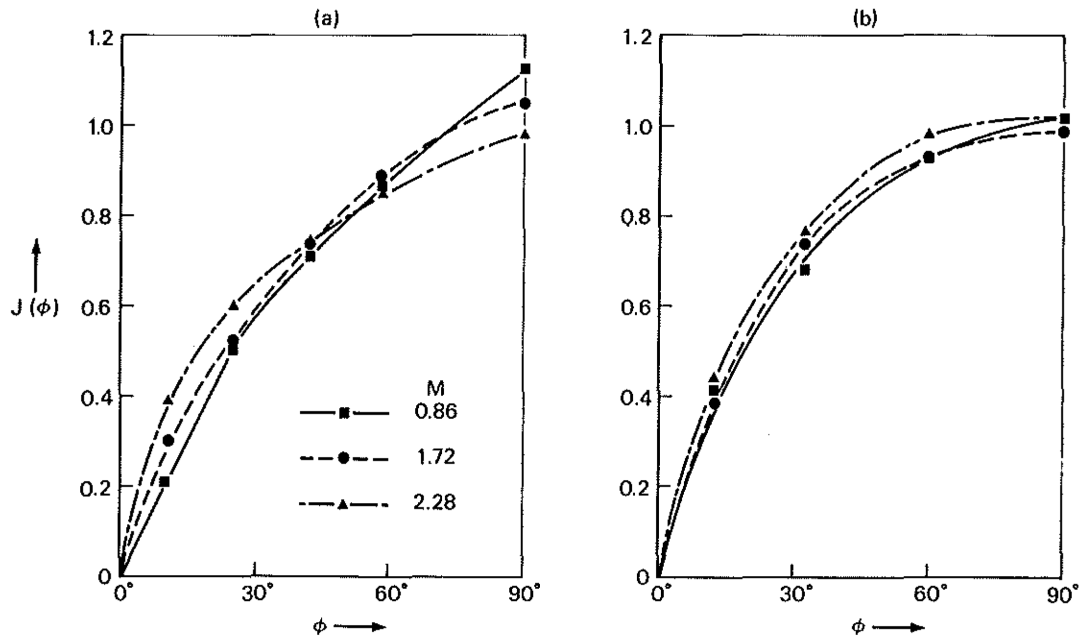


Figure 1. Variation of correction factor $J(\phi)$ with angle of opening, for ventilation due to stack effect through (a) side-mounted casement and (b) center-pivoted windows

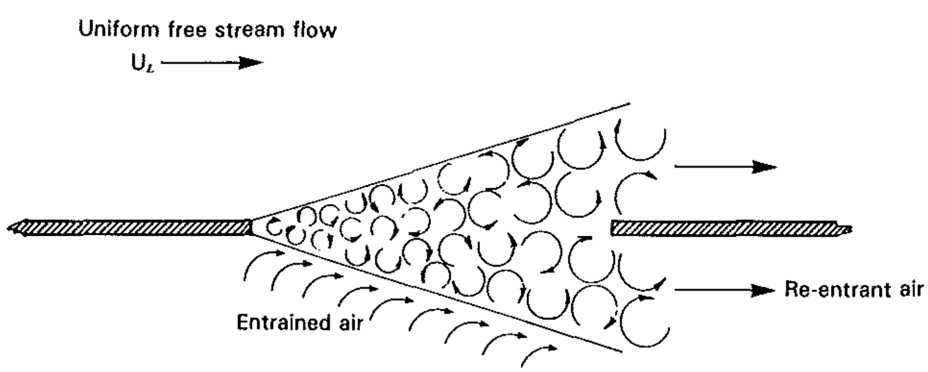


Figure 2. Schematic representation of a two-dimensional turbulent mixing layer

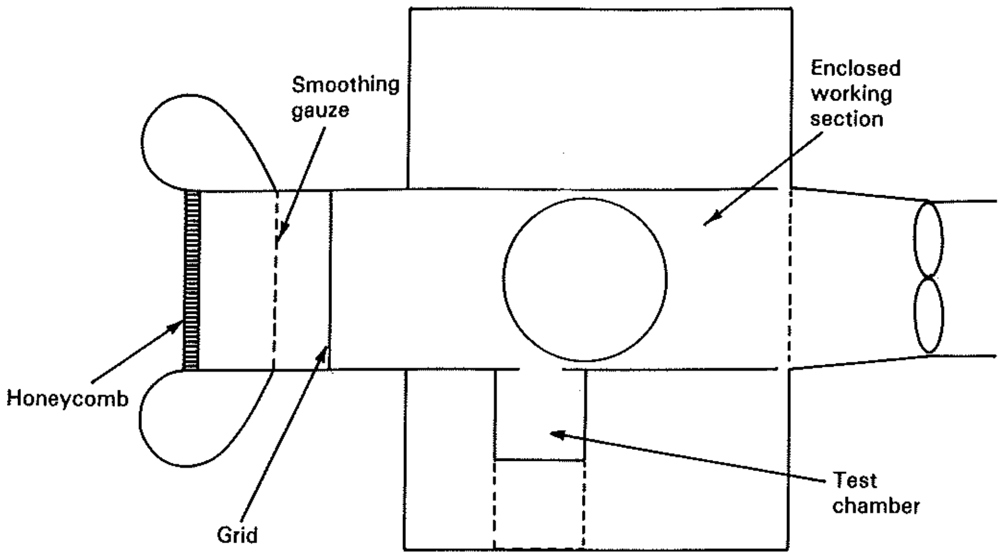


Figure 3. Schematic plan view of wind tunnel and test chamber

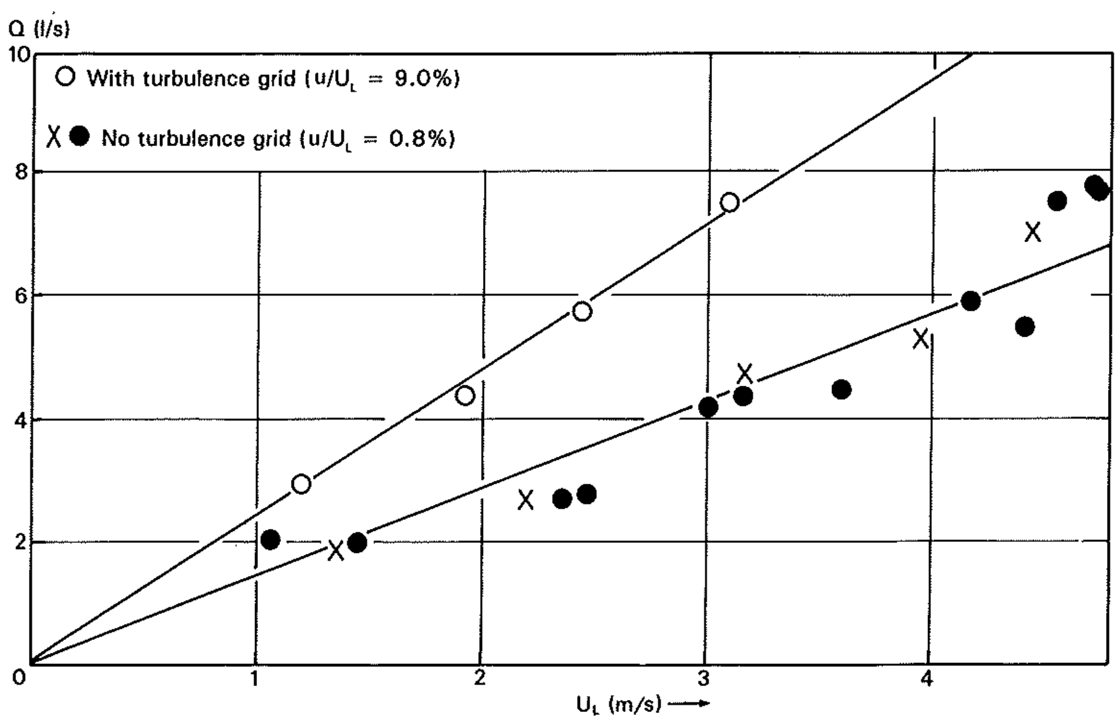


Figure 4. Variation of air exchange rate, Q, with tunnel velocity, U_L, for a plane, square opening, size 10 in x 10 in, with and without enhanced freestream turbulence

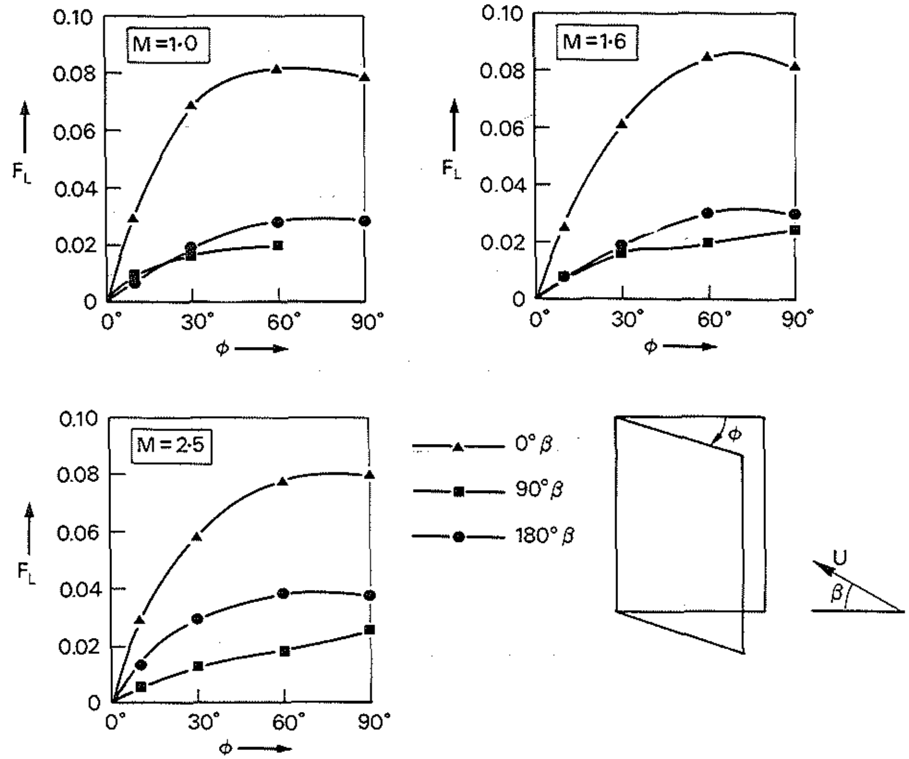


Figure 5. Variation of flow number, F_L, with angle of opening, ϕ, and flow direction, β, for model side-mounted casement windows of aspect ratios, M = 1.0, 1.6, and 2.5

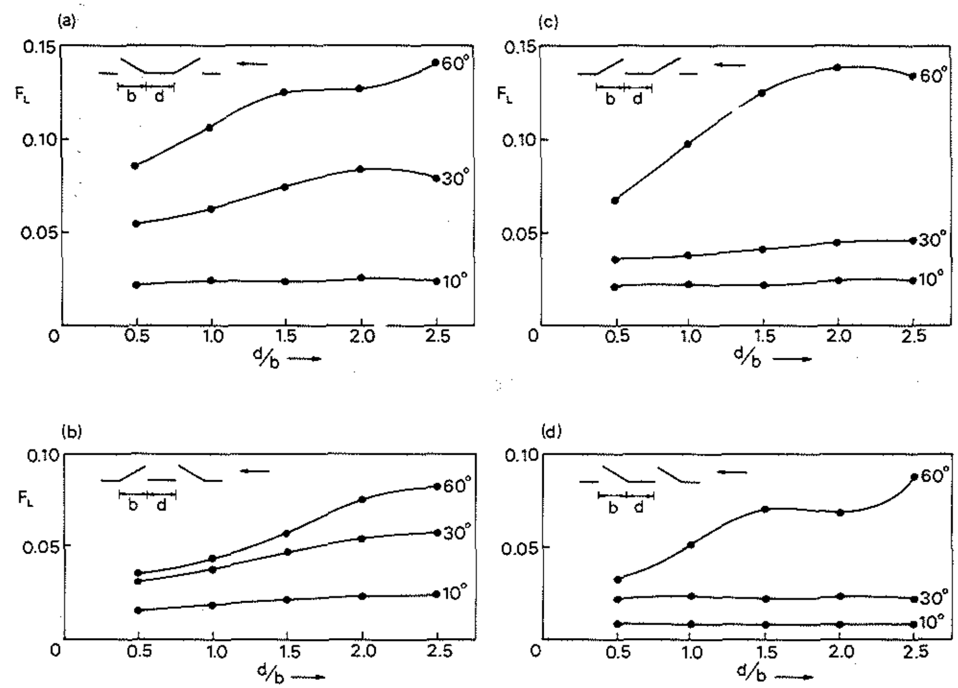


Figure 6. Variation of flow number, F_L, with angle of opening, ϕ, and spacing, (d/b), for four arrangements of two model side-mounted casement windows, each of aspect ratio M = 1.25

Figure 7. Building 1, general view

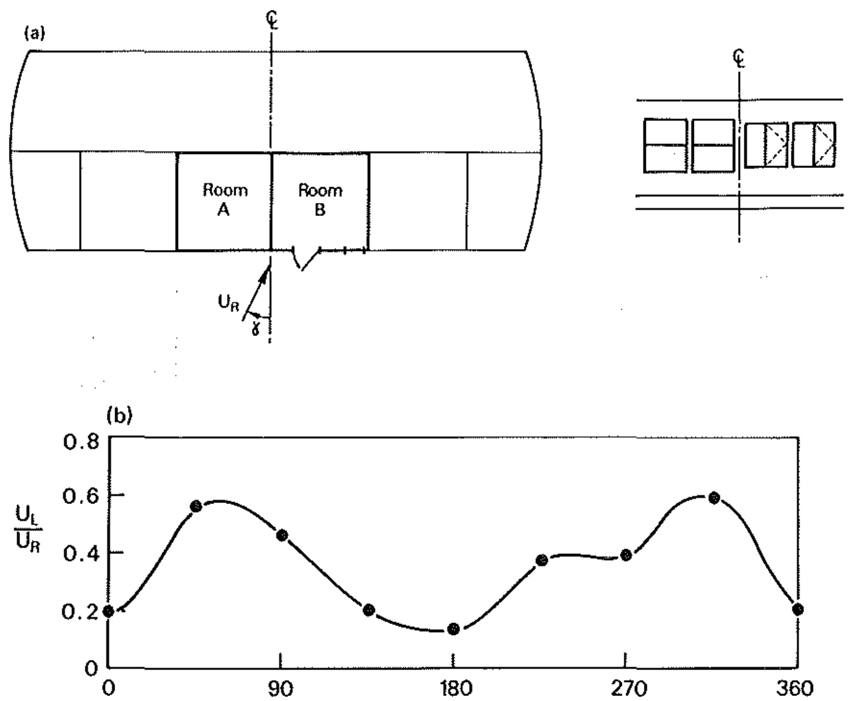
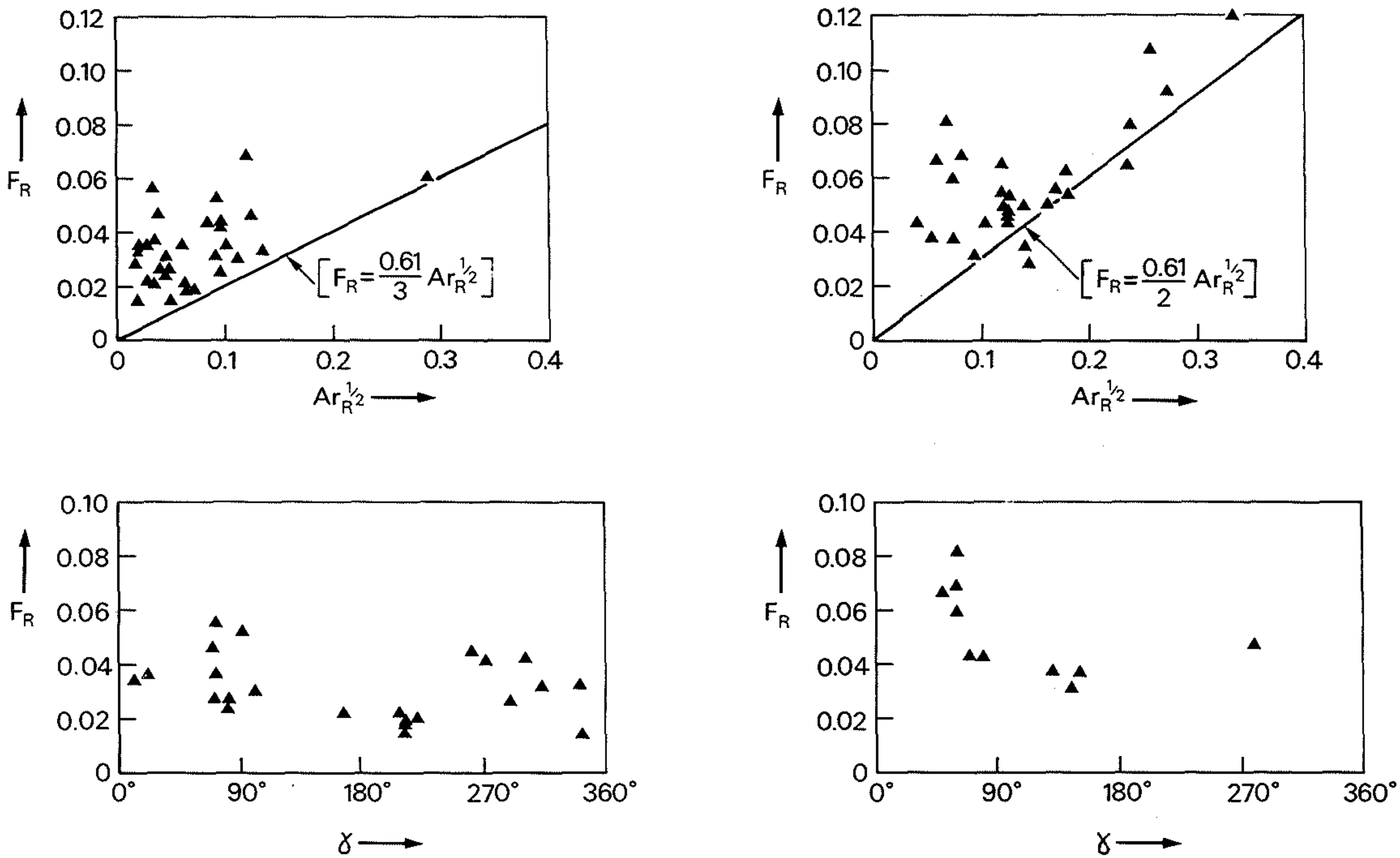


Figure 8. (a) Building 1, plan view and window arrangement; (b) Building 1, variation of local flow speed, U_L, with wind direction, γ, at the position of the windows in room A



(a) Single plane opening

(b) Two vertically separated plane openings

Figure 9. Building 1: variation of flow number, F_R, with Archimedes Number, Ar_R, and wind direction, γ, for (a) a single plane opening and (b) two vertically separated plane openings

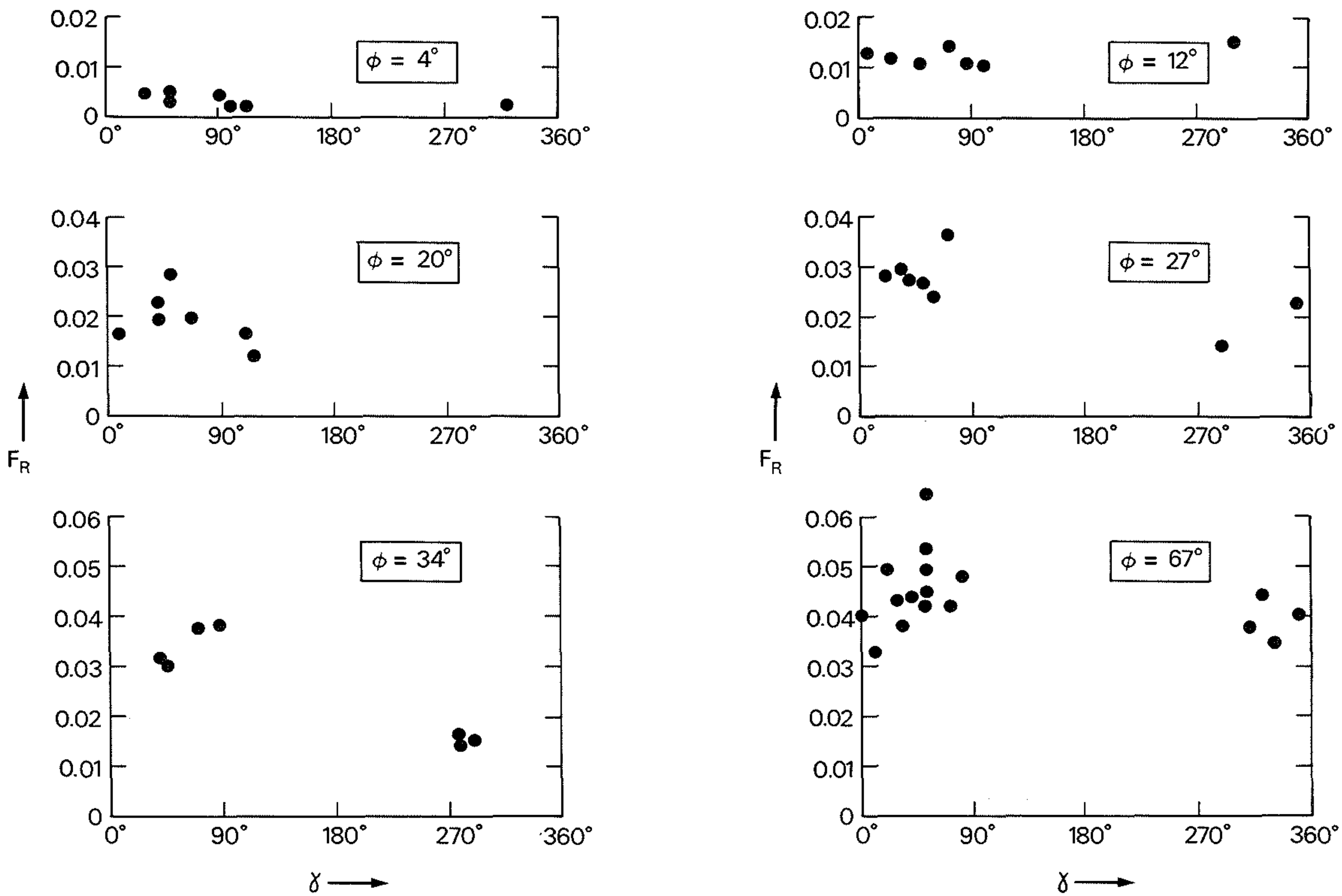


Figure 10. Building 1: variation of flow number, F_R, with wind direction, γ, for a single side-mounted casement window, at angles of opening, ϕ, of 4°, 12°, 20°, 27°, 34°, and 67°

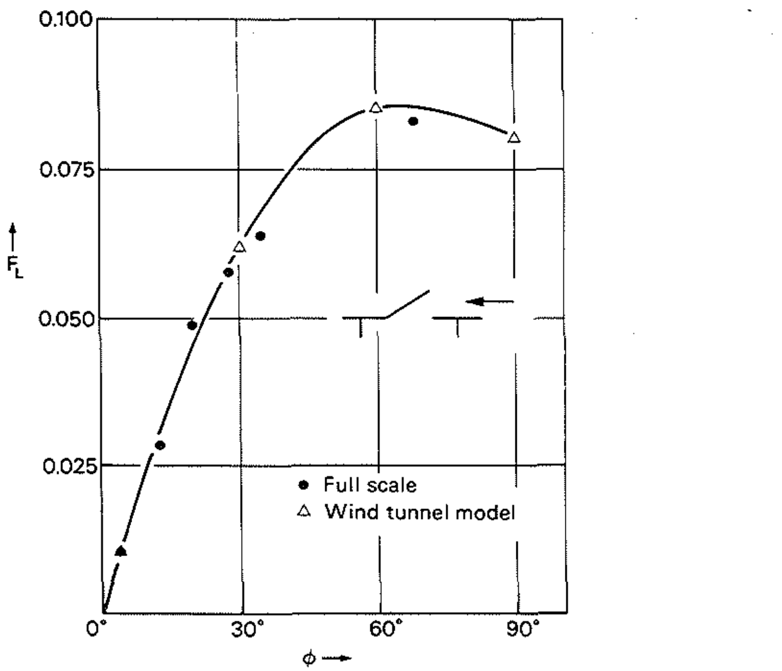
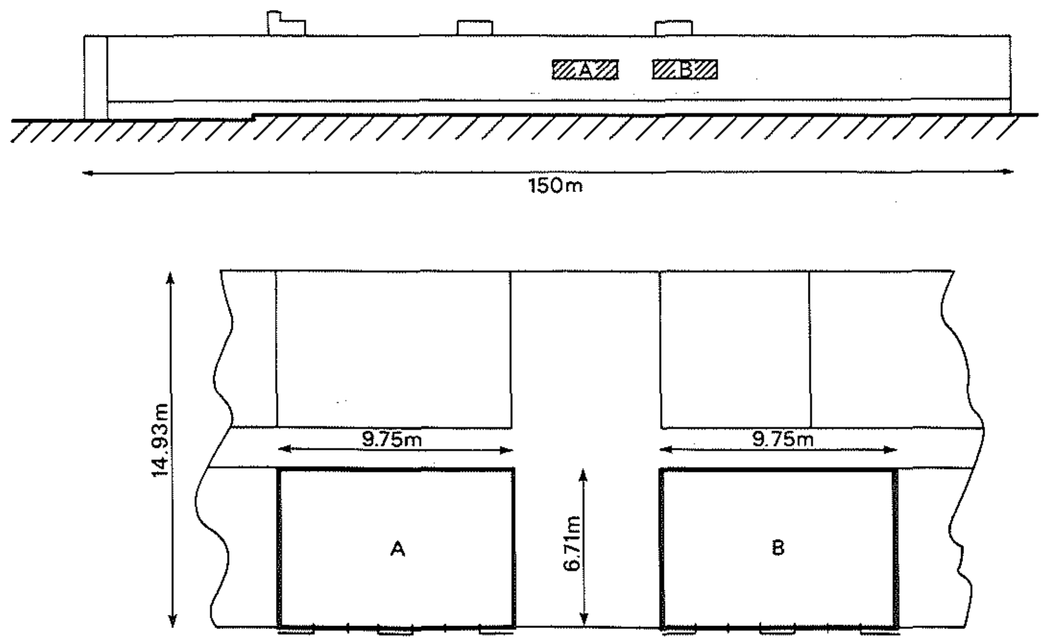


Figure 11. *Comparison of full-scale and wind tunnel model results for a side-mounted casement window, showing the variation of flow number, F_L, with angle of window opening, ϕ*



Room A Volume = 180m³ , Vertical sliding window

Room B Volume = 180m³ , Slide mounted Casement

Figure 12. *Building 2: (a) elevation showing position of rooms A and B; (b) plan view of rooms A and B*

Figure 13. Building 2, arrangement of windows and combinations of openings used in the field measurements: (a) room A, vertical sliding windows; (b) room B, side-mounted casement windows

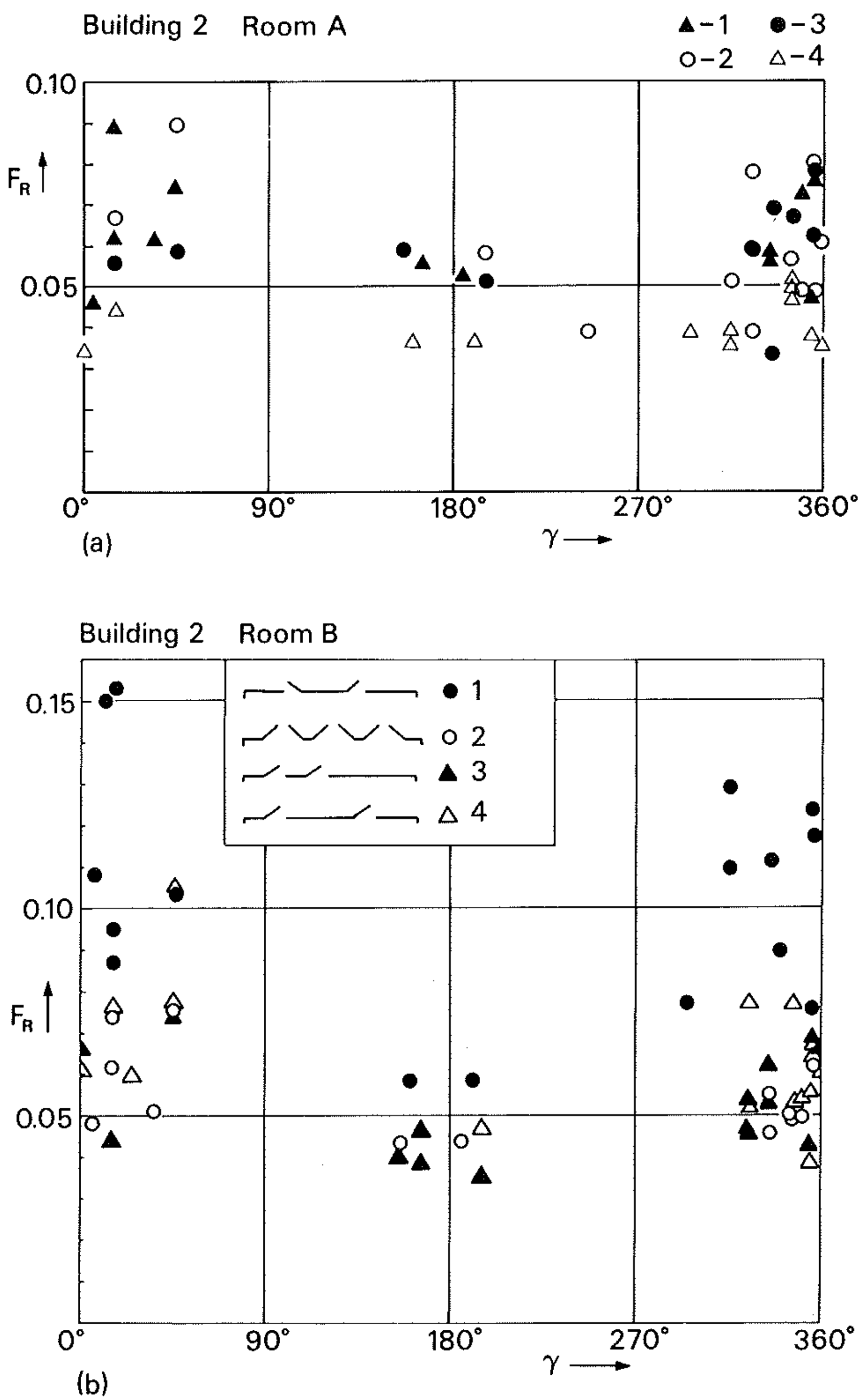


Figure 14. Building 2, variation of flow number, F_R, with wind direction, γ, for different combinations of open window: (a) room A, vertical sliding windows; (b) room B, side-mounted casement windows