1876

Acc 1281

No. 2924

A Correlation for Estimating Wind Ventilation

C.K. Krishnakumar, Ph.D. **R.H. Henninger**
ASHRAE Member

C.K. Schafer **S.F. Fields, Ph.D.** **D.A. Bettge**
ASHRAE Associate Member

ABSTRACT

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, and wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used in these tests. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas, and the velocity of the approach wind. Results were compared with those projected from available correlations for general type buildings.

INTRODUCTION

Estimating wind-induced ventilation rates in buildings or evaluating building designs with regard to wind ventilation remains a difficult problem due to the lack of reliable calculational models. Variables that affect wind-induced ventilation in buildings are many, and the interactions between them are difficult to predict. In the 1960s, many studies of wind-induced ventilation in full-scale fallout shelters were conducted by the Office of Civil Defense (OCD). These studies utilized a relationship similar to the one given in the ASHRAE Handbook-1977 Fundamentals (ASHRAE 1977, Chapter 21) for estimating wind-induced ventilation in buildings:

$$Q = EAV \tag{1}$$

where
Q = Air volume flow rate (cfm)
E = Effectiveness factor
A = Free area of inlet openings (square feet)
V = Wind speed (feet per minute)

The value of the effectiveness factor is given as 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for winds at other angles. When the inlet and outlet areas are not equal, the flow increases in a nonlinear fashion with the area ratio (ASHRAE 1977, Chapter 21, Figure 12). The ASHRAE model leaves room for guessing and gives results that differ considerably from experimental values as indicated by the tests on full-scale buildings conducted by OCD (Madson et al. 1964; Madson et al. 1965; Meier et al. 1966; Henninger et al. 1966) and wind tunnel tests on scale models of fallout shelters conducted for the Federal Emergency Management Agency (Krishnakumar et al. 1983).

In an earlier study (Krishnakumar et al. 1982; Krishnakumar et al. 1983), the authors developed a wind tunnel scale model test method to predict wind-induced ventilation rates in shelter buildings. The method, which involves flow tracing and motion photography, was refined in a later study (Krishnakumar et al. 1984), the results of which are presented here and applied to shelters with different areas and distributions of wall openings. Based upon results of these

---

C.K. Krishnakumar, Senior Engineer; R.H. Henninger, Manager, Energy Applications; C.K. Schafer, Energy Systems Engineer; S.F. Fields, Manager, Engineering Mechanics and Materials; GARD, Niles Illinois. D.A. Bettge, Research Physical Scientist, Civil Defense Directorate, FEMA, Washington, D.C.

THIS PREPRINT FOR DISCUSSION PURPOSES ONLY. FOR INCLUSION IN ASHRAE TRANSACTIONS 1985, V. 91, Pt. 2. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329. Opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors) and do not necessarily reflect the views of ASHRAE.

tests, a correlation was generated to predict wind-induced ventilation rates in shelter buildings under varying wind conditions.

SHELTER MODELS

The objective of this study was to determine a correlation between the wind-induced ventilation rate in a bermed[*], above-ground, fallout shelter and the independent variables of wind velocity, total area of wall openings, and the ratio of opening areas on the windward and leeward sides. This objective was achieved by conducting wind tunnel tests on models of fallout shelters with five distinct opening configurations. All shelters had the same length, width, and height as the one in the earlier study (full-scale dimensions: 48 ft (14.63 m) long x 32 ft (9.75 m) wide x 12 ft (3.66 m) high). The total area of openings varied from 2.50% to 3.44% of the wall surface area. Since all five shelters had the same overall dimensions, the different opening configurations were obtained from the same basic model by using close-fitting wedges and plates to block off, open up, or modify one or more of the openings. The basic model was fabricated to a length scale of 1:36 (model:full-scale) from 3/16 inch (4.76 mm) thick aluminum plates and tempered glass sheets. (For a discussion of scaling considerations, Krishnakumar et al. 1982.) The plates and wedges were machined to close tolerances to minimize errors in the results due to air leakage. A clear polycarbonate sheet (1/32 inch (.08 mm) thick) was screwed to the bottom of the model and served as its floor. Lines parallel to the walls were scribed on this sheet 3/16 inch (4.76 mm) apart on either side of each wall opening to serve as distance markers. Six 300 watt photographic lights were encased inside the simulated earth berms to illuminate the interior of the shelter model. Figure 1 is a photograph of the basic model with the aluminum wedges partially withdrawn. Figures 2 - 6 show the interiors of the models with the different opening configurations. Table 1 summarizes the dimensional data for the models.

MODEL TESTS

By using a counterjet manifold system (Krishnakumar et al. 1983), the velocity profile in the tunnel's boundary layer was made to conform to a power law distribution given by $V_1/V_2 = (Y_1/Y_2)^{1/3.35}$ where V_1 and V_2 are the velocities at heights Y_1 and Y_2, respectively, from the tunnel floor. The exponent 1/3.35 corresponds to those recommended for wind velocity profiles

TABLE 1

Dimensional Characteristics Of Shelter Configurations

Shelter Configuration	Total Wall Area	Windows		Doors		Total Opening Area	Area Ratio (Opening/ Wall)
		No.	Area	No.	Area		
	ft^2/ (m^2)		ft^2/ (m^2)		ft^2/ (m^2)	ft^2/ (m^2)	
A	1920/ (178.4)	3	27/ (2.51)	1	21/ (1.95)	48/ (4.46)	0.0250
B	1920/ (178.4)	2	18/ (1.67)	2	42/ (3.90)	60/ (5.57)	0.0313
C	1920/ (178.4)	4	36/ (3.35)	1	21/ (1.95)	57/ (5.30)	0.0297
D	1920/ (178.4)	4	36/ (3.35)	1	21/ (1.95)	57/ (5.30)	0.0297
E	1920/ (178.4)	5	45/ (4.18)	1	21/ (1.95)	66/ (6.13)	0.0344

---

[*] Bermed with earth or other suitable material to reduce radiation.

in suburbs of cities (Davenport 1960). Model ventilation rates for the various approach stream velocities were then determined by performing the following three series of tests. In the first series of tests, air volume flow rates passing through calibration tubes attached to the leeward openings of the models were correlated with measurements of axial velocities at a section 15 diameters downstream of the leading edge of these tubes. In the next series of tests, actual values of ventilation rates through the models were determined with tubes attached to the leeward openings, for different velocities of the approach airstream. The third series of tests was performed to determine the "tube correction factor", which is defined as the factor by which the ventilation rates with the tubes in place (obtained from the second series of tests) should be multiplied to get actual values of model ventilation rates.

Test Series 1 - Anemometer Calibration for Volume Flow Rate

These tests were conducted to establish a correlation between the actual air volume flow rates through the shelter model and the axial velocities measured in a calibration tube attached to a leeward opening when all other openings were closed. Velocity measurements were made by a hot-wire anemometer located approximately 15 diameters downstream of the inlet of the calibration tube. The correlation was obtained by forcing metered air volume flow rates through one of the wall openings and simultaneously recording anemometer readings of air velocities in the tube. Figure 7 shows the calibration test setup. When multiple leeward openings were present, calibration tubes were attached to all of them. It was established that the airflow rates through the model could be obtained as the sum of the flows through all the tubes.

Test Series 2 - Determination of Air Volume Flow Rates with Tubes at Leeward Openings

In this series of tests, values of ventilation rates through the model were determined with calibration tubes attached to the leeward openings for different velocities of the approach airstream. Air volume flow rates were obtained from measurements of axial velocities in each of the leeward tubes and the calibration curve established in Test Series 1.

Test Series 3 - Determination of Tube Correction Factor

The object of these tests was to determine values of the tube correction factor, which is defined as the ratio of the model ventilation rate obtained without calibration tubes at the leeward openings to that obtained with the tubes. The tube correction factor was calculated as the ratio of the average flow velocity at the main windward opening obtained without tubes at the leeward openings to that obtained when tubes were attached to the leeward openings. Average flow velocities through the main windward opening were obtained by determining the average velocities of neutrally buoyant tracer bubbles passing through that opening using motion photography. The details of flow tracing and data reduction are described elsewhere (Krishnakumar et al. 1983).

RESULTS AND DISCUSSION

Based on the model test data, the following correlation was obtained between the dependent variable, model ventilation rate, and the independent variables of approach wind velocity, windward opening area, and a factor F, whose value depends on the ratio of the leeward opening area to the windward opening area:

$$Q = 0.31 \times A_w \times V_m \times F \qquad (2)$$

where Q is the ventilation rate, cfm (m^3/s).
A_w is the area of openings on the windward sides, square feet (square metres). (Openings on walls parallel to the direction of the approach airstream should be taken as leeward openings.)
V_m is the speed of the approach airstream corresponding to the meteorological wind speed, which is normally measured at 30 feet (10 metres) above the ground, FPM (m/s)*.
F is a Flow Correction Factor that gives the increment or decrement in flow due to unequal areas of the windward and leeward openings. Values of F are obtained from Figures 8a and 8B. This data should not be extrapolated.

---

* The value of V_m in the tests varied from 3.5 FPS (1.07 m/s) to 13.75 FPS (4.19 m/s).

Equation 2 is a sample, linear relation that enables one to estimate shelter ventilation rate as a function of the approach wind speed, area of windward openings, and the ratio of areas of leeward and windward openings. For a shelter of given total wall opening area, the ratio of leeward to windward opening area depends on the relative wind angle*. Equation 2 was obtained by correlating experimental data from all five shelter models. As shown in Figure 9, the correlation is extremely good at the higher values of the approach wind speed. However, the correlation is weak at the lowest value of the approach wind speed tested. This is partly due to the inaccuracies in the measurement of axial velocities in the calibration tubes at such low values (less than 50 feet per minute) and partly to the simple linear form of the correlation chosen.

Equation 2 is similar in form to Equation 1 referred to in the introduction. For buildings with equal areas of windward and leeward openings (for which the factor F in Equation 2 equals unity), the constant of proportionality in Equation 2 agrees with that of Equation 1 for the case of diagonal winds. However, for perpendicular winds, values given by Equation 1 are substantially larger (up to 100%). It may be noted that Equation 2 was developed for shelters with earth berms. The berms probably aid ventilation when the approach wind is at an angle by acting as flow deflectors. This, together with the fact that the distribution of windward and leeward opening areas is often more favorable at diagonal winds than at perpendicular winds, is probably the reason why shelter ventilation rates at diagonal winds are often equal to or greater than those for perpendicular winds.

Use of Equation 1 for estimating building ventilation rates raises some ambiguities. ASHRAE 1977 and ASHRAE 1981 define the independent variable A as the area of the inlet wall openings, whereas an earlier edition of ASHRAE Fundamentals (1972) defines it as the smaller of the inlet and outlet opening areas. Further, when openings are present in walls parallel to the direction of the approach wind, one is left guessing as to the proper value of this variable. In Equation 2, the variable A_w always denotes the total area of the windward openings. The increment or decrement of flow due to unequal areas of windward and leeward openings is accounted for by the Factor F. For a building with unequal areas of openings on opposite walls, Equation 1 gives the same value of ventilation rate when the relative wind angle is changed by 180°. This was not found to be true for the shelter models studied. Equation 2, in which values of the factor F are taken from two different curves (Figures 8a and 8b) depending on whether the ratio (A_l/A_w) is greater than or less than unity, is found to give better correlation with experimental values. However, extrapolation of these curves beyond the ranges of the ratio (A_l/A_w) indicated in these figures is not recommended.

Figures 10a-10d show that maximum values of ventilation rate per unit area of wall openings are obtained when the windward opening area is about 50% of the total. For all five models, the highest values of ventilation rate per unit area of wall openings were obtained when the windward opening area was between 30% and 60% of the total opening area. This observation was true for all values of the approach wind speed tested. It may be inferred that if openings are distributed over the walls so that the windward opening area is between 30% and 60% of the total opening area at any value of the relative wind angle, the ventilation rate per unit area of openings will not be very sensitive to the actual location and area of the individual openings. However, the air distribution inside the whelter, which is not discussed in this paper, is likely to depend upon the location and area of the individual openings.

REFERENCES

ASHRAE. 1972. ASHRAE handbook - 1972 fundamentals. Chapter 19, "Infiltration and natural ventilation." New York: American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc.

ASHRAE. 1977. ASHRAE handbook - 1977 fundamentals. Chapter 21, "Infiltration and Ventilation." New York: American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc.

ASHRAE. 1981. ASHRAE handbook - 1981 fundamentals. Chapter 22, "Ventilation and infiltration." New York: American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc.

---

* The variable relative wind angle defines the direction of the approach wind relative to a reference axis of the building.

Davenport, A.G. 1960. "Rationale for determining design wind velocities," Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, pp. 39-61, May.

Henninger, R.H., et al. 1966. "Natural ventilation test of an aboveground fallout shelter in Chicago, Illinois," GATX Interim Report, GARD 1268-81, SRI, Subcontract No. B-64220(4949A-16)-US, DDC No. 641701, August.

Krishnakumar, C.K., et al. 1982. "Evaluation of wind ventilation in buildings by wind tunnel tests," ASHRAE Transactions, Vol. 88, Part I.

Krishnakumar, C.K., et al. 1983. "Evaluation of shelter ventilation by model tests," FEMA Contract EMW-C-063, FEMA Work Unit 1217I, for Federal Emergency Management Agency, GARD INC., March.

Krishnakumar, C.K., et al. 1984. "Evaluation of shelter ventilation by model tests - Option 2," FEMA Contract EMW-C-063, FEMA Work Unit 1217I, for Federal Emergency Management Agency, GARD, September.

Madson, C.A., et al. 1964. "Natural ventilation test of an aboveground fallout shelter in Bozeman, Montana" GATX Interim Report, MRD 1195-56-2, SRI Subcontract No. OCD-OS-62-134, DDC No. 453070, November.

Madson, C.A., et al. 1965. "Natural ventilation test of an aboveground fallout shelter in Baton Rouge, Louisiana," GATX Interim Report MRD 1268-20, SRI Subcontract No. B-64220(4949A-16)-US, DDC No. 456893, January.

Meier, H.A., et al. 1966. "Natural ventilation test of an aboveground fallout shelter in Evanston, Illinois, GATX Interim Report, GARD 1268-51, SRI Subcontract No. B-64220(4949A-16)-US, January.

TABLE 1

DIMENSIONAL CHARACTERISTICS OF SHELTER CONFIGURATIONS

Shelter Configuration	Total Wall Area ft^2/ (m^2)	Windows		Doors		Total Opening Area ft^2 (m^2)	Area Ratio (opening/ wall)
		No.	Area ft^2/ (m^2)	No.	Area ft^2/ (m^2)		
A	1920/ 178.4	3	27/ 2.51	1	21/ 1.95	48/ 4.46	0.0250
B	1920/ 178.4	2	18/ 1.67	2	42/ 3.90	60/ 5.57	0.0313
C	1920/ 178.4	4	36/ 3.35	1	21/ 1.95	57/ 5.30	0.0297
D	1920/ 178.4	4	36/ 3.35	1	21/ 1.95	57/ 5.30	0.0297
E	1920/ 178.4	5	45/ 4.18	1	21/ 1.95	66/ 6.13	0.0344

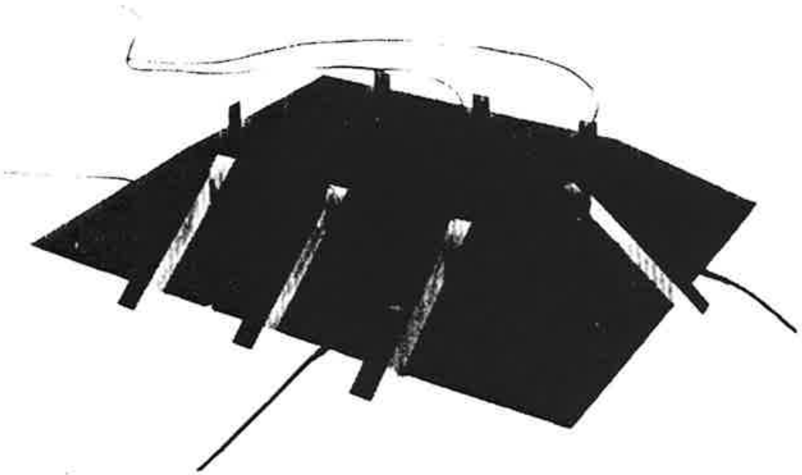


Figure 1. Shelter model with wedges partially pulled out

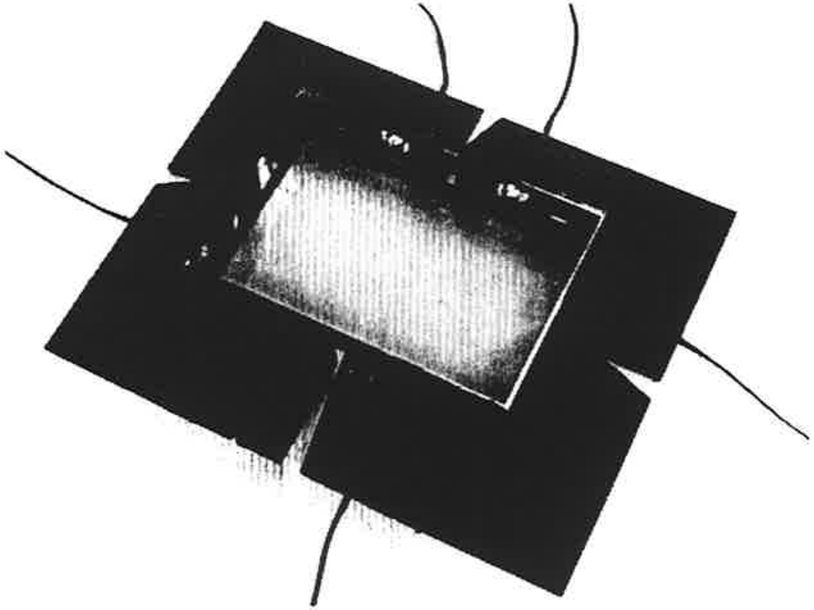


Figure 2. Model configuration – A

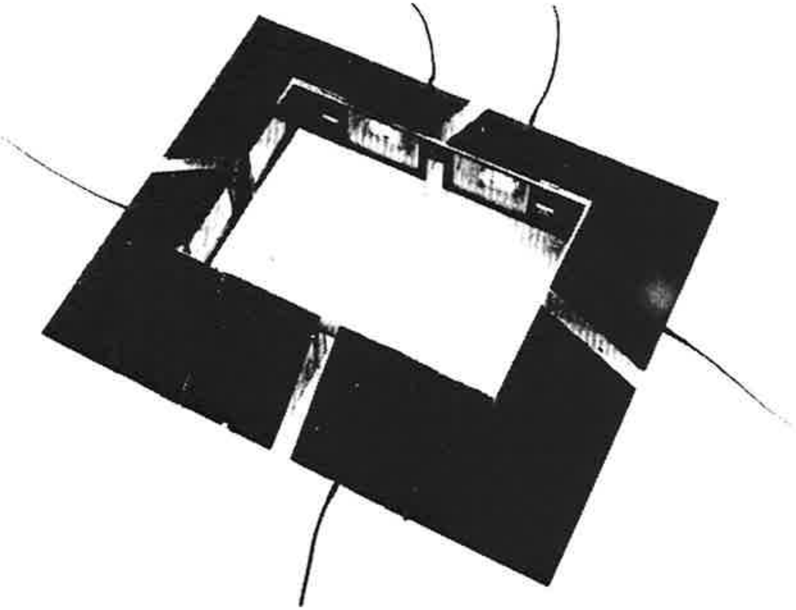


Figure 3. Model configuration – B

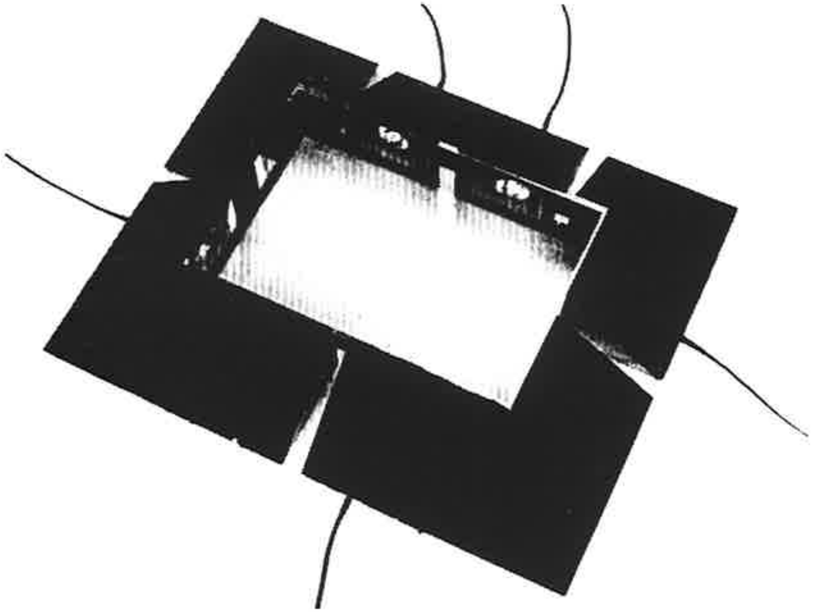


Figure 4. Model configuration – C

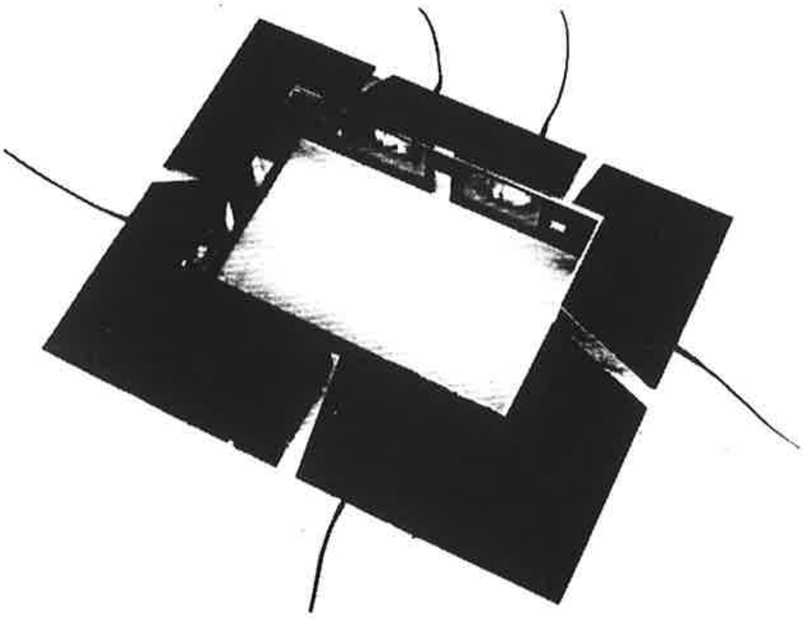


Figure 5. Model configuration - D

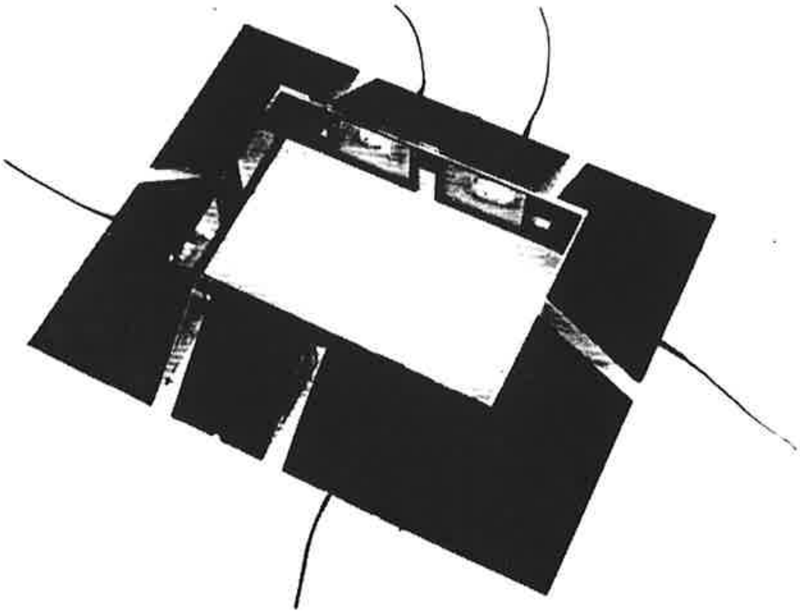
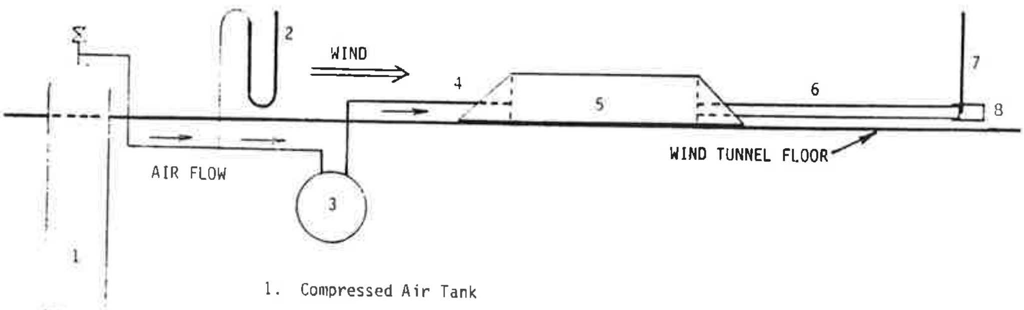
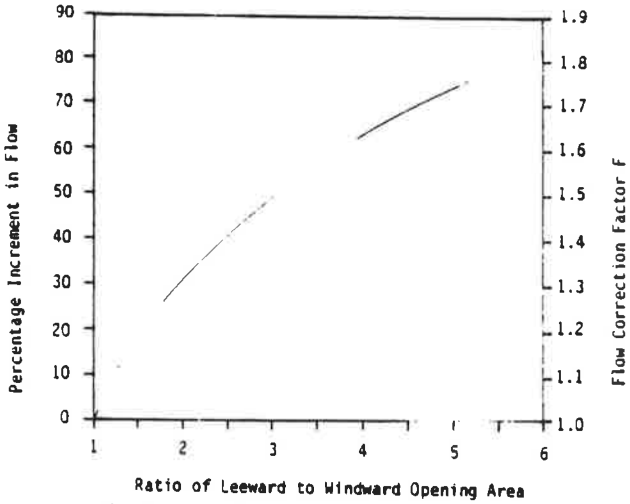


Figure 6. Model configuration - E

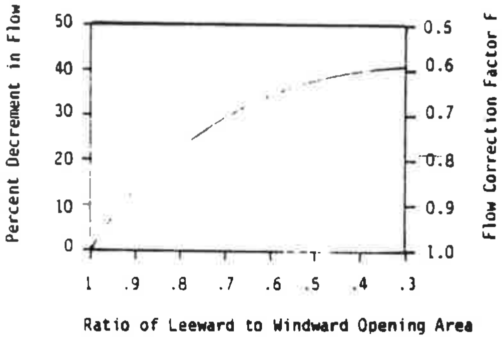


1. Compressed Air Tank
2. U-Tube Manometer
3. Sprangue Wet Test Gas Meter
4. Flexible Air Intake Tube
5. Shelter Model
6. Calibration Tube
7. Hot-Wire Anemometer Probe
8. Extension Tube

Figure 7. Setup for anemometer calibration



(a) For Area Ratios ≥ 1.0



(b) For Area Ratios ≤ 1.0

Figure 8. Flow change due to unequal areas of windward and leeward openings

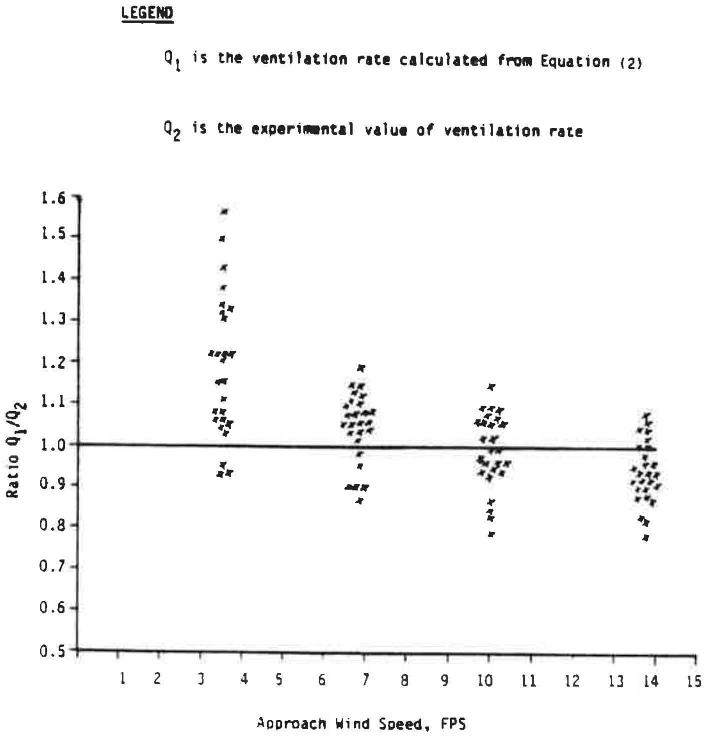


Figure 9. Calculated versus measured ventilation rates

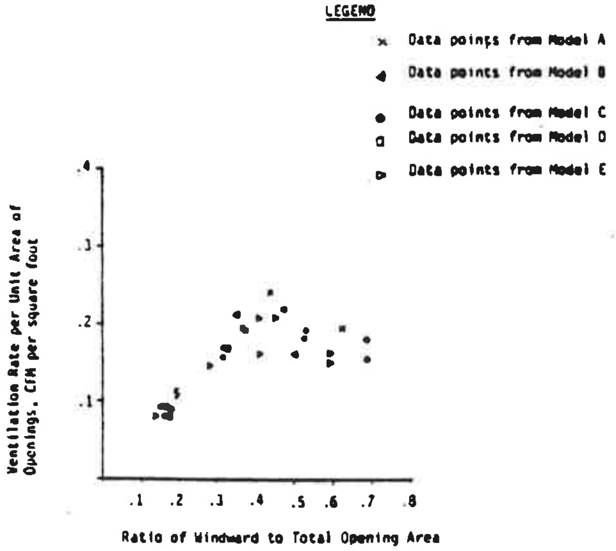


Figure 10a. *Influence of opening distribution on ventilation rate per unit opening area, wind speed 210 FPM*

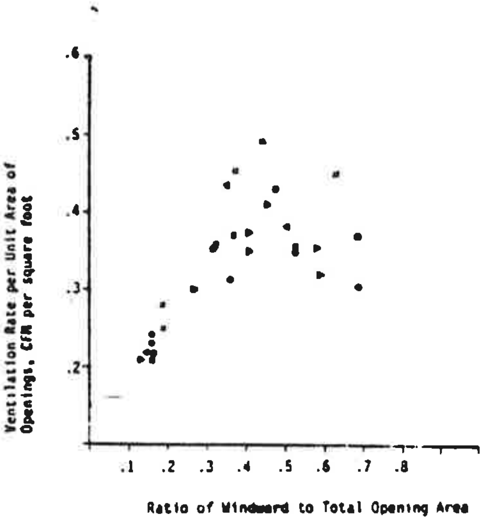


Figure 10b. *Influence of opening distribution on ventilation rate per unit opening area, wind speed 410 FPM*

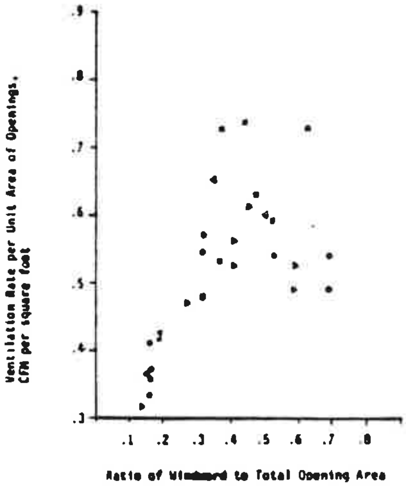


Figure 10c. *Influence of opening distribution on ventilation rate per unit opening area, wind speed 600 FPM*

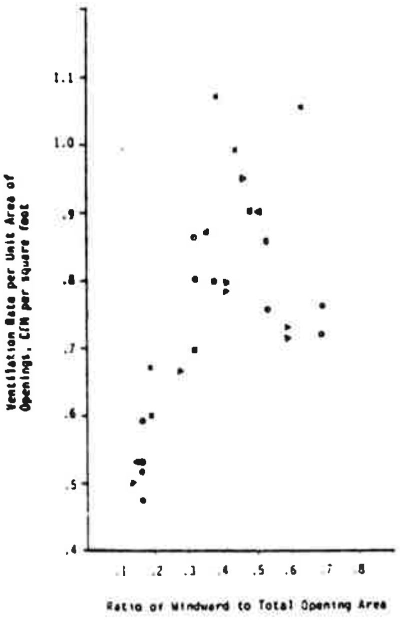


Figure 10d. *Influence of opening distribution on ventilation rate per unit opening area, wind speed 825 FPM*