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WIND TUNNEL AND FULL-SCALE DATA ON AIRFLOW FROM NATURAL VENTILATION AND CEILING FANS

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ABSTRACT

The state of the art on predicting airflows from natural ventilation is discussed. The usefulness and limitations of wind-tunnel-derived building pressure coefficient data in predicting airflow are presented. Actual measured full-scale field data are provided to show the effects of atmospheric turbulence, window type, and insect screening on airflow. Also presented are airflow and airspeed data from ceiling fans.

INTRODUCTION

The ever-increasing cost of air conditioning has prompted us to research ventilative cooling as a supplement to mechanical cooling for southeastern residences. Other aspects of our work have been recently presented (see Fairey et al. 1985, a parametric study of ventilative cooling energy savings, and Kerestecioglu et al. 1985, for algorithms to predict moisture effects in ventilative buildings). This paper reviews the state of the art of algorithms to predict natural ventilation airflow rates and also presents data on ceiling fan performance.

In order to integrate natural ventilation with mechanical cooling and heating systems, one is usually forced into designing buildings with a relatively small window area, say, 10% to 15% of the floor area. Otherwise mechanical conditioning costs may become excessive. With small amounts of window area, one can achieve 10 to 40 air changes per hour (ach) in typical U.S. suburbia (Chandra 1983). Although this amount of airflow may be sufficient for building cooling, i.e., rejecting heat from the building, it is totally inadequate to provide sufficient airspeeds for human comfort.

Consider a typical house of dimensions 50 ft x 30 ft x 8 ft (15.2 m x 9.1 m x 2.4 m) with windows on the large walls of the house. If the entire house volume participates in the air exchange, the airspeed in the main part of the room will be only 15 ft/min (0.08 m/s) at 30 air changes per hour (ACH). Even if we assume only 50% of the room volume participates in the air exchange (due to dead corners, furniture, etc.) the airspeed will only be double the previous value. This is pretty close to negligible air motion for cooling people. For the effective cooling of people, airspeeds in the range of 100-400 ft/min (0.5-2 m/s) are desirable. Air circulation fans (ceiling fans, oscillating portable fans, etc.) must, therefore, be employed for people cooling in a naturally or fan forced ventilated house.

Our computer studies indicate that ventilative cooling savings are highly sensitive to building airflow rate, at the low air change rates (5 to 30) likely to occur in practice (Fairey et al. 1985). Validated algorithms to predict airflow from natural ventilation are

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thus necessary to predict energy savings and develop design tools. In addition, development of designs to augment airflow in buildings and low-cost test methods to evaluate innovative designs are also necessary. See Chandra (1985) for a summary of research conducted at FSEC on the latter topics.

Air flows through a building due to wind-induced pressure differences acting across the inlets and outlets of a building. The stack effect can also cause natural ventilation. However, the stack effect is weak, and it works only in the daytime when ambient temperatures are generally higher than the desired indoor temperature and ventilation is not desired. Thus, stack ventilation is not discussed further. The wind engineering and infiltration research communities have generated a large data base of building pressure coefficient (C_p) distributions by testing solid building scale models in boundary-layer wind tunnels (see for example, Allen 1984). Natural ventilation researchers (e.g., Aynsley 1977; Vickery 1983) have proposed that the airflow through naturally ventilated buildings be also calculated from solid building C_p data.

This paper summarizes the usefulness and limitations of C_p data in predicting natural ventilation. The effect of wind turbulence on airflow at low wind speeds or in poorly ventilated situations will be discussed. Full-scale data on airflow reductions due to awning type windows and due to insect screening are also presented. Finally, data from ceiling fans will be given.

USE OF BUILDING PRESSURE COEFFICIENTS (C_p) IN PREDICTING NATURAL VENTILATION AIRFLOWS

In 1982 and 1983 an investigation was performed on the adequacy of C_p data to predict natural ventilation airflows. The results are detailed in a contract report by Vickery (1983) and are summarized below for wider dissemination of his interesting results.

We first discuss the flow computation method proposed by Vickery. The assumptions of this method are:

1. No stack effect.
2. Same internal pressure in all rooms of the building implying zero pressure drop in rooms. This also implies all the doorways inside the building are open.
3. Fluctuating pressure effects not accounted for.
4. Perfect mixing occurs in the building.

Most of these assumptions are satisfied by a well-ventilated building. Even if there is some uncertainty, given the level of data available, it is our opinion that Vickery's procedure is the optimum for present computational purposes. We note that for infiltration calculations, more sophisticated models are available, e.g., a multi-cell model (Etheridge and Alexander 1980), which accounts for stack effects and fluctuating pressures but requires a higher level of data input.

The Vickery model starts with the standard orifice flow equation through the i^{th} aperture:

$$\Delta Q_i = C_{di} A_i \, V_r (C_{pi} - C_{pI}) \,/\, \left| C_{pi} - C_{pI} \right|^{1/2} \tag{1}$$

<u>where</u>

- ΔQ_i = flow through the i^{th} aperture
- C_{di} = discharge coefficient for the i^{th} aperture accounting for flow direction (the same aperture could have different C_d depending on whether it was an inlet or an outlet)
- A_i = area of i^{th} aperture
- V_r = reference wind speed at some height, e.g., 10 m
- C_{pi} = pressure coefficient = $(P_i - P_s)/\ 1/2\ \rho V_r^2$
- $P_i - P_s$ = pressure difference between the surface pressure tap and free stream static pressure
- ρ = air density
- $C_{pI} = P_I/(1/2 \rho V_r^2)$ = internal pressure coefficient
- P_I = internal pressure

The numerator and denominator are written to account specifically for inflows and outflows. Equation 1 is nondimensionalized by V_r and a reference area A such that it is recast as:

$$\Delta C_{Qi} = C_{di} \frac{A_i}{A} \cdot (C_{pi} - C_{PI}) / \left| C_{pi} - C_{PI} \right|^{1/2} \quad (2)$$

From the continuity equation

$$\sum_{i=1}^{N} \Delta C_{Qi} = 0 \quad (3)$$

where N = number of openings

An iterative solution (since C_{PI} is unknown) is obtained as follows:

I) Define two starting values of C_{PI} as

$$(C_{PI})_1 = (\Sigma C_{pi})/N$$

$$(C_{PI})_2 = (C_{PI})_1 + 0.01$$

and compute the corresponding values of net inflow Σ_1, and Σ_2.

II) Compute a new estimate (C_{PI}) from the relationship;

$$(C_{PI})_K = (C_{PI})_{K-1} + \frac{(\Sigma \Delta C_{QI})_{K-1}}{(\Sigma \Delta C_{QI})_{K-2} - (\Sigma \Delta C_{QI})_{K-1}} \cdot \left[(C_{PI})_{K-1} - (C_{PI})_{K-2} \right]$$

In the above K is the iteration number.

III) Compute the corresponding value of the net inflow,

$(\Sigma \Delta C_{QI})$ and test $\left| (\Sigma \Delta C_{QI})_K \right| < 10^{-4}$

YES; put $C_{PI} = (C_{PI})_K$ and compute the elemental flow coefficients ΔC_{QI}

NO; return to (II)

The flow into the building can then be evaluated by summing ΔC_{QI} over all positive values while the flow through a given surface can be obtained by an algebraic sum over the regions comprising that surface.

Note that for the simple case of one inlet and one outlet, there is no need to solve for C_{PI}. C_{PI} can be eliminated from the inflow and outflow equations and the flow determined in one step.

To assess the adequacy of this model, Vickery conducted tests using a boundary-layer wind tunnel.

Vickery constructed two identical models, one solid and another with varying wall porosities for the long walls (see Figure 1). There was a capability also to add extended eaves and wingwalls and have an aperture at the roof ridge. The airflow through the ventilated model was directly measured in the wind tunnel. The flow was then compared to that calculated using C_p data as measured on the identical solid-body model. Figure 2 shows the comparisons for the cross ventilated case with 21% wall porosity.

For larger porosities, the solid body C_p data overestimates the actual flow. As Vickery explains, the "through" flow through the porous building decreases the pressure difference between the windward and leeward sides and thus the actual flow is reduced. Vickery suggests a simple correction factor to account for this;

$$C_Q = C_{QO}/(1 + C_{QO}) \quad (4)$$

where C_Q refers to the actual flow for large porosities and C_{QO} is the flow computed by using solid body pressure data per the procedure described above. The Vickery conclusions are re[illegible]ted below:

1. At low values of the internal flow coefficient (C_Q<0.1 or a wall porosity less than about 25% on two opposite faces) the internal flows can be predicted from the external pressure distribution measured on a solid or sealed building provided the openings are on walls. The level of accuracy that can be achieved (given reliable pressure data and reliable estimates of the discharge coefficients) is, typically, 10%.

2. If a simple correction term is added to account for the influence of the "through-flow" on the pressure field, then the internal flows can be predicted with acceptable accuracy (about 10%) for values of C_Q up to about 0.3, which, for openings on two walls, corresponds to a wall porosity of about 70%.

The situation changes however when one analyzes ridge-vented models. A number of schemes have been suggested to accomplish whole building ventilation using roof-ridge-level apertures (Chandra 1985). Ridge venting was tested by using a solid leeward wall and using a porous windward inlet and ridge outlet. Figure 3 shows the results. Solid body C_p data significantly overpredict the flow even for small flow coefficients. Vickery suggests that this may be due to the flowfield around the roof ridge being modified by the airflow from the ridge vents.

Our conclusion from these windtunnel tests and other field tests (Chandra 1983) is that if C_p data for the building are known and local wind speeds can be accurately estimated, then for strong winds (e.g., local 10 m wind speed greater than 6 mph (2.7 m/s)) and apertures located on the walls, natural ventilation airflows can be predictd to about 10% using the Vickery procedure for wall porosities up to 70%. In addition to the difficulties of obtaining good C_p data for typical buildings in the presence of adjacent buildings, etc., we note that procedures to predict local wind speeds from airport data are not validated. To our knowledge, the terrain-correction factors relating airport winds to other terrains were developed in Europe for strong winds when wind loading of buildings becomes a concern. To the authors' knowledge, the validity of the terrain correction factors for normal wind speeds have not been established.

Effects of Wind Turbulence

When wind speeds decrease, fluctuations in the wind direction and turbulence generally increase. Under this rather common condition, airflow becomes highly erratic and cannot be well predicted using C_p data.

Figure 4 presents recent full-scale data on this topic. Natural ventilation airflow was continuously measured in the southeast room of a Passive Cooling Laboratory (PCL) with only one awning window for inlet and two ceiling apertures for the outlet. Airflow was continuously measured by three hot film probes located at the end of a flow-straightening section downstream of the window. The flow-straightening section consisted of a four-feet-long flow-contracting section made out of smooth foil-faced rigid insulation. The outlet of this section had an area equal to 50% of the window area. At the end of this a honeycomb was used to further straighten the flow.

Data were sampled every 10 seconds and averaged for 15-minute periods. Each 15-minute average is represented by a point in Figure 4, which plots the average inlet to site 10 meter wind speed ratio for nine days in August 1985. The horizontal axis represents wind direction measured clockwise from north. As the window was on an east wall (azimuth=90^o) it was an inlet window for the wind directions plotted. To obtain trends in the data for different wind speed regimes, the data were separated in 2 mph (0.9 m/s) bins and third-degree least-squares fits to the data were obtained. The results are shown in Figure 5. We see that for WS >6 mph (2.7 m/s) the data are unique, but we get different lines for lower wind speeds. Moreover, as seen in Figure 4, the data scatter increases substantially at these low wind speeds.

During summer nights, in many parts of the Southeast, the local winds are below 6 mph (2.7 m/s). Thus, wind turbulence is likely to create a significant uncertainty in predicting natural ventilation airflows.

Airflow Reductions Due to Awning Windows and Insect Screening

The airflow-calculation procedure is valid for rectangular apertures in the wall without screening. In practice, insect screening is routinely used. Also, since sliding windows have

50% closed area, we recommend projection or awning windows (fully operable windows with two or three horizontally pivoted sashes) for rain protection and maximizing natural ventilation. Measurements were made to determine the airflow reduction from fully open awning windows (open at an angle of 30 degrees to horizontal) and from a 60% porous insect screen. Airflows were measured using the same technique as outlined in the previous section. For wind speeds below 6 mph (2.7 m/s) at the 10 meter level, the airflow had a lot of scatter and did not exhibit discernable trends. For wind speeds greater than 6 mph, Figure 6 presents the least-squares fit curves through the data for the three cases tested. The ratio of airflow in the presence of window and screens to the case of no window was calculated from the data in Figure 6 and plotted as a function of wind incidence angle (which is wind direction shown in Figure 6 minus 90 degrees, the azimuth of the window). This ratio was fairly constant with respect to wind incidence angle. Table 1 presents this ratio, called the airflow correction factors.

TABLE 1

Airflow Correction Factors

Fully open awning windows, no screen	0.75
Awning window and 60% porosity screen	0.65
60% porosity insect screen, no window (from above data, i.e., 0.65/0.75)	0.85

For wind speeds greater than 6 mph (2.7 m/s) the airflow computed from C_p data can be multiplied by Table 1 factors to get actual airflow through different window and insect screening combinations. It is very interesting to note that the actual airflow through screens is more than would be predicted by considering the geometrical porosity of the screen. The airflow correction factor for the 60% porosity screen is 0.60 if only geometric porosity is considered.

FULL-SCALE DATA FROM CEILING FANS

As noted earlier, we recommend the use of ceiling fans to cool people in naturally ventilated homes. Ceiling fans also allow the air-conditioning thermostat to be set up by at least 4 F (2.2°C) saving substantial amounts of cooling energy.

We have measured airspeeds provided by a ceiling fan, and Figure 7 shows the results. It is seen that the ceiling fan provides effective cooling in a circular area whose diameter is twice the blade diameter of the fan. We have noted from personal experience that large top-of-the-line ceiling fans can provide air motion in larger areas up to a radius of 8 to 10 ft (2.4-3 m) from the fan center. Figure 8 shows the airspeeds measured under the fan as the fan blade clearance (the distance between blades and the ceiling) was varied in one-inch increments. The airspeeds were measured by omnidirectional hot-film-type airspeed probes with a 2 mm spherical measurement tip. This probe is claimed to be accurate at low airspeeds such as those reported here. We see that there is a noticeable drop in airflow below 6 in (.15 m). For clearances greater than that, the airspeeds away from the fan and under the fan center are largely unaffected. However, the airspeeds at fan blade edge continues to increase. Since most people sit or sleep between fan edge and one fan diameter, it seems that the maximum clearance physically possible would be the recommended blade clearance.

The circles and squares represent airspeeds measured for two ceiling-hugger fans. Ceiling-hugger fans are fans designed to have a small clearance (about 6 in or .15 m) between the fan blade and the ceiling. In general the airspeeds from ceiling huggers are significantly worse than the regular fan. For the 6 in (.15 m) clearance the regular fan was much better than the ceiling hugger with the same clearance. This might be due to improper blade angle settings for the ceiling huggers. It appears that the average air motion from ceiling huggers will be about 40% less than that from regular fans.

The Attic-Coupled Ceiling Fan

A frequent problem in the southeastern U.S. during summertime is the low wind speed at night. Even if the homeowners are willing to tolerate the humidity, the low nighttime wind speeds result in very poor natural ventilation. This can result in house temperatures at night 5 F (2.8°C) or more warmer than outside even if the windows are open. Similar situations exist at moderate wind speeds if the room is not cross-ventilated (e.g., bedrooms with only one window). One way to alleviate this situation is to use whole house fans. An alternative solution, which uses ceiling fans coupled to the attic, has been proposed by Chandra. In this application, the ceiling fan provides both airspeed for people cooling and airflow for building cooling.

This concept uses operable ceiling vents above the ceiling fan as shown in Figure 9. The ceiling vents should be positioned so that the vents are near the tip of the fan blades. The shutters should open as shown to maintain only a small clearance between the blade and shutter. The insulated vent shutters are manually operated and are kept closed during the daytime (hot attic) so that the ceiling fan can be operated normally. Data on a full-scale house show that a moderately vented attic (with soffit vents and gable vents) will cool down to within 1-2 F (.5-1°C) of the ambient temperature during the sleeping hours of 11 p.m. - 7 a.m. (Chandra and Kerestecioglu 1983). At that time the ceiling vents can be opened. Then the ceiling fan pulls in cool air from the attic and exhausts it through an open window in the bedroom. If the night is windy then, even without the fan running, sufficient cross-ventilation can be attained from one window and the ceiling vents. Note that this concept is especially useful for rooms with only one window.

This concept might also work in winter to draw hot attic air into the house during winter daytime. Shutters should seal tight to prevent nighttime heat loss from the room to the cooled attic. Due to the risk of pulling in loose fibers from the attic, it is recommended that this concept not be used in attics with blown-in insulation.

Tests of this concept have been conducted in one room of a passive cooling laboratory. On a windless (wind speed at 10 meters less than 0.5 mph (.22 m/s)) morning without the ceiling fan running and the vents open, natural ventilation produced only 4 air changes/hour. With the ceiling fan running, the airflow through the room increased to 20 air changes/hour. The airflow was measured by traversing the wall aperture at 12 locations by an airspeed probe. The first author may be contacted for further details of this test.

On windless summer nights, a normal room with ceiling fans running is likely to have 4-5 air changes/hour resulting in a room temperature about 5 F (2.8°C) higher than outside. This 5 F value has been measured in the field in real houses. So if the night temperature is 78 F (25.5°C), the room will be around 83 F (28.3°C). With this new concept with 20 air changes per hour, the room temperature will be only 2 F (1.1°C) higher, i.e., 80 F (26.7°C), a comfortable temperature with the ceiling fan running if the homeowner does not mind the humidity.

CONCLUSION

We conclude that building pressure (C_p) distributions can predict natural ventilation airflows through windows in windy locations (i.e., periods when site 10 meter winds are greater than 6 mph). As wind speed decreases, the effect of wind turbulence becomes prominent and must be accounted for. Exactly how is not clear yet. Low wind speeds, projection or awning windows, and insect screening are common in naturally ventilated residences and all tend to reduce the airflow from what would be predicted using C_p data. Quantitative full-scale data on the magnitude of airflow reductions from these effects have been presented.

Ceiling fans are very popular and highly recommended by the authors to cool people in Southern residences. Full-scale measurements on airspeed data from ceiling fans are presented. A new concept for night ventilation using ceiling fans has been proposed.

Accurate prediction of airflows is necessary to correctly estimate energy savings from natural ventilation. As a first, step the existing world-wide C_p data base needs to be consolidated in a computer-friendly format. This work is currently being performed by us under ASHRAE funding.

Full-scale tests need to be performed to measure natural ventilation airflows in real houses to validate the calculated algorithms. Additionally, validated algorithms need to be developed to predict local site wind speeds from airport wind data during low wind speed conditions.

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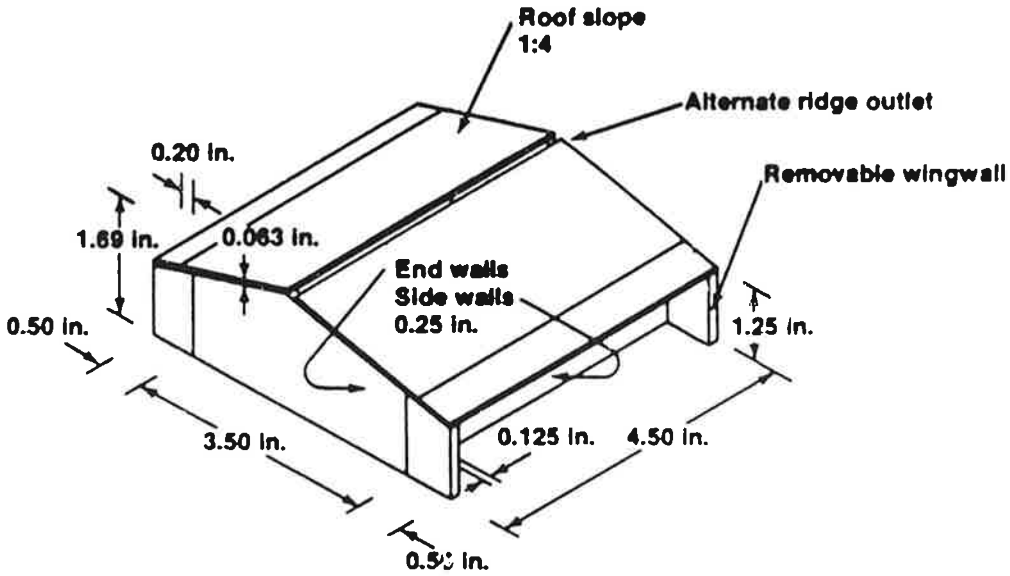

Figure 1. 1:100 scale model used in wind tunnel tests

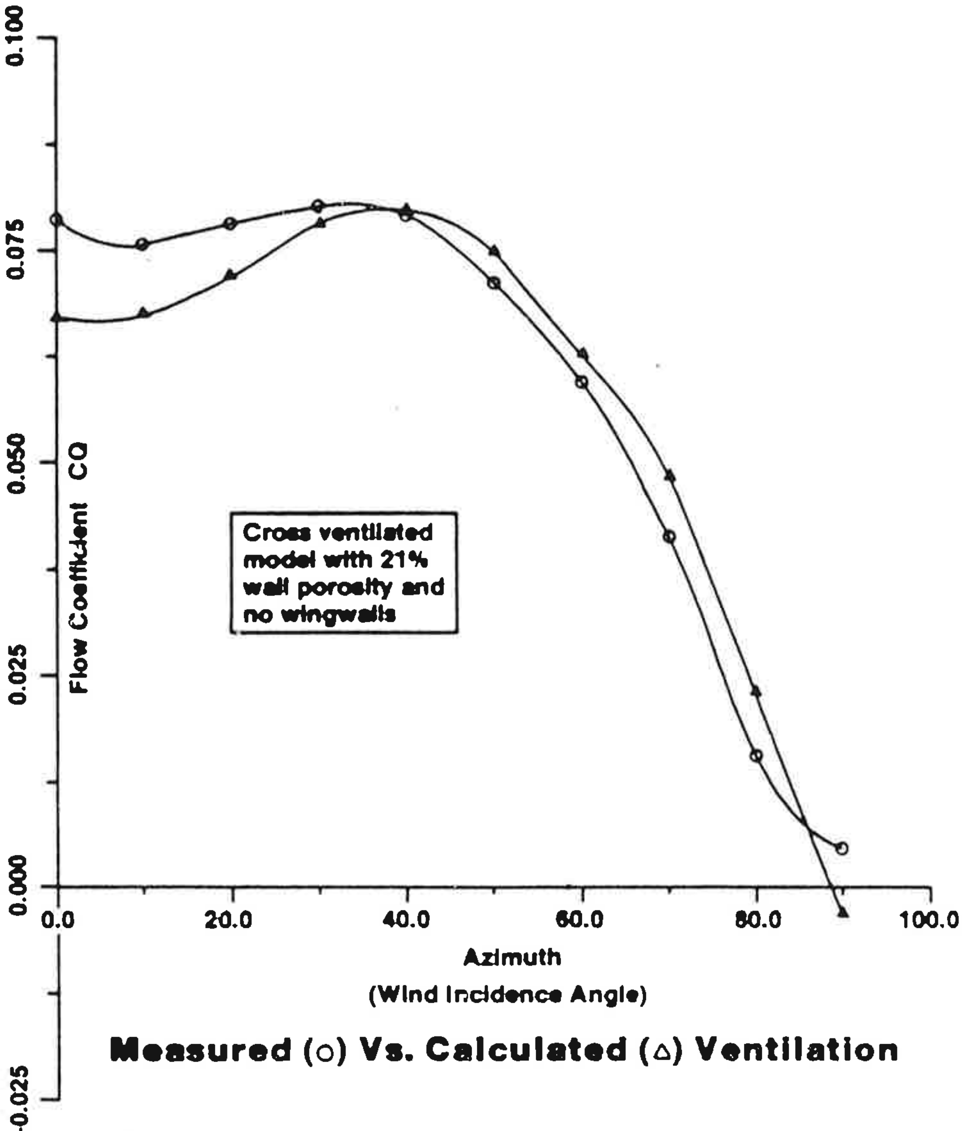

Figure 2. Comparison of measured and predicted ventilation airflow for a cross-ventilated model

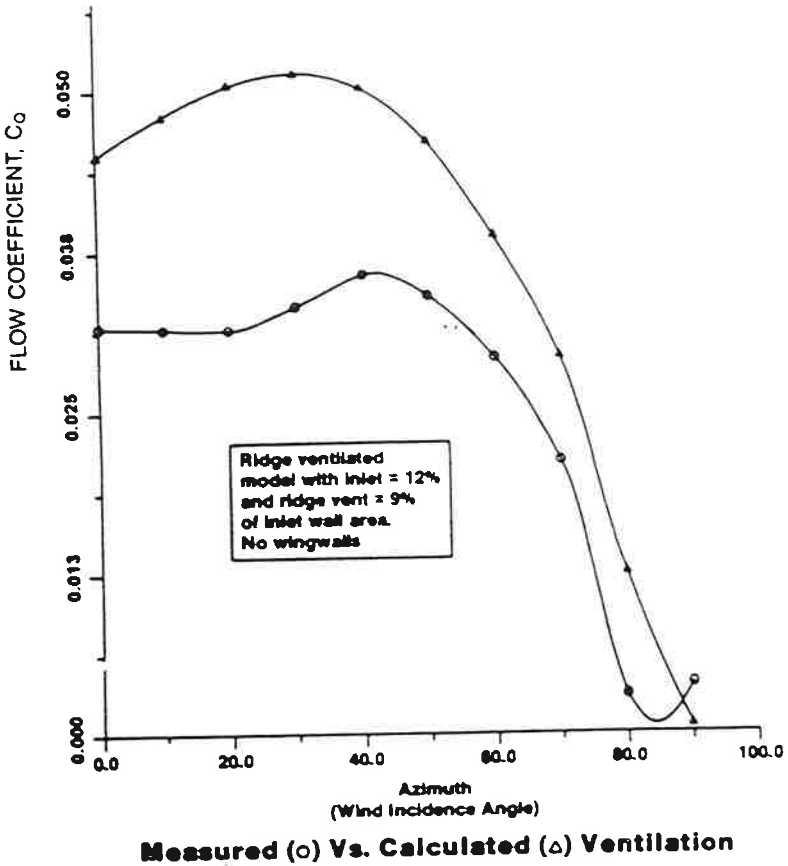

Figure 3. Comparison of measured and predicted ventilation airflow for a ridge-ventilated model

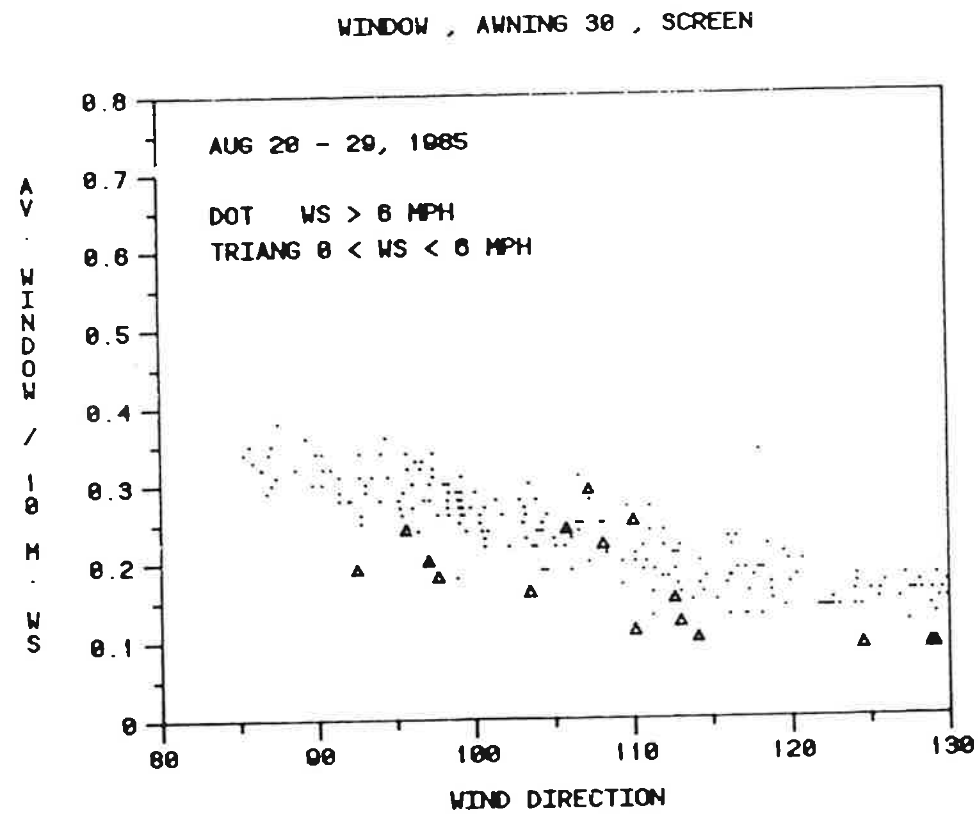

Figure 4. Measured airflow through an insect-screened, fully open awning window. The data scatter is due to atmospheric wind turbulence

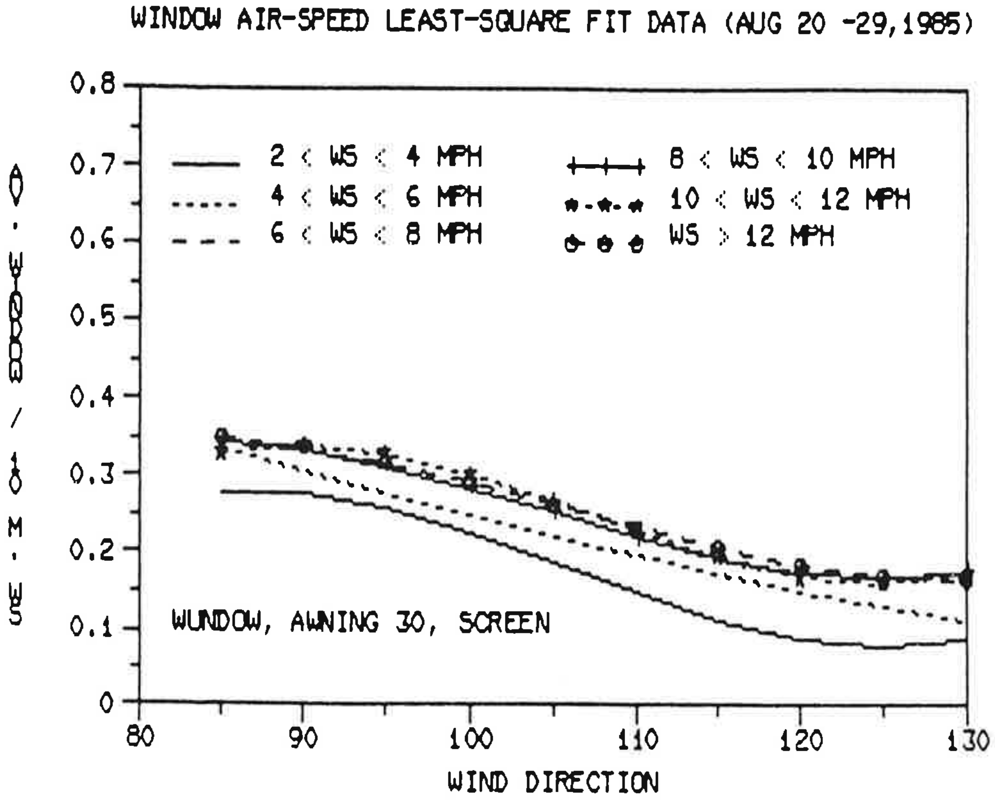

Figure 5. Least-square curve fit lines for data presented in Figure 4. Note the different data trends at low windspeeds

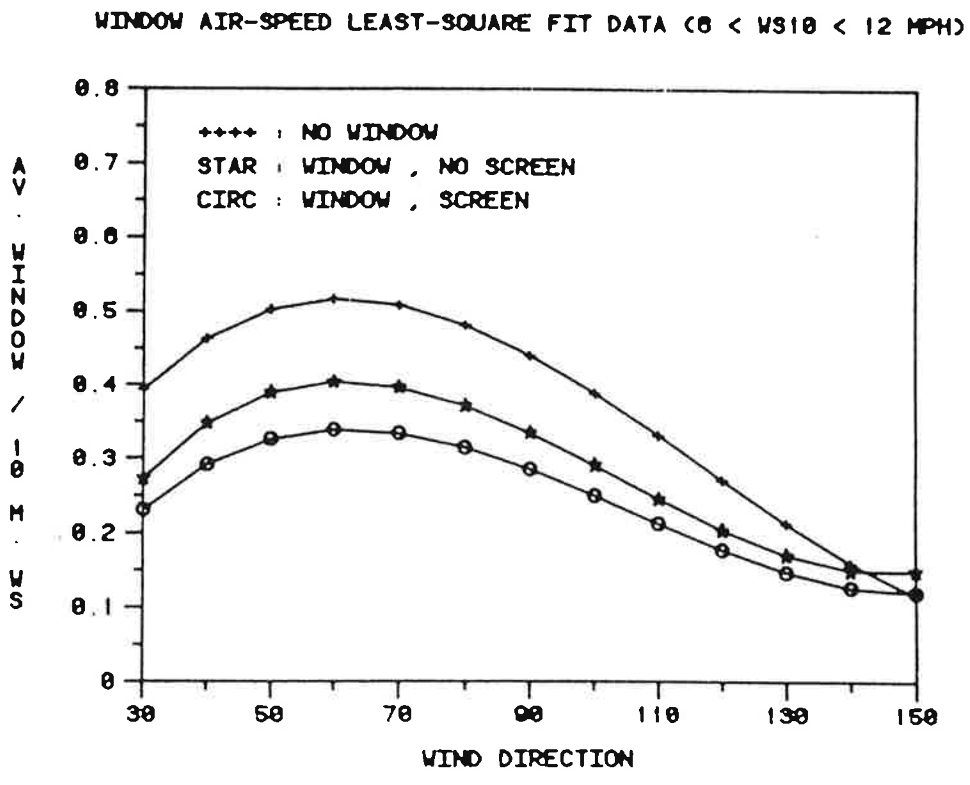

Figure 6. Airflow reductions due to awning windows and insect screening

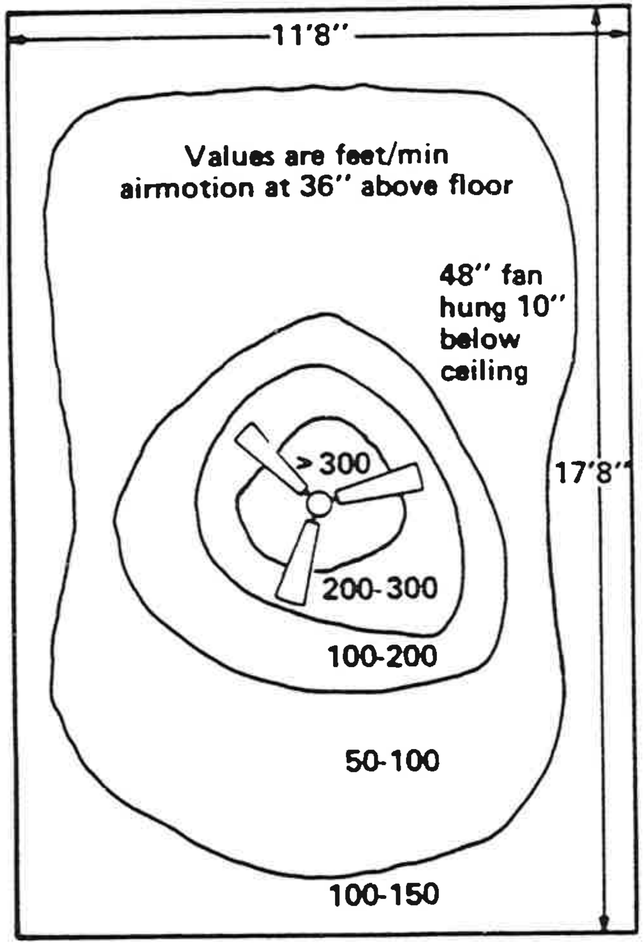

Figure 7. Airspeed contours from a ceiling fan in a room with no furniture

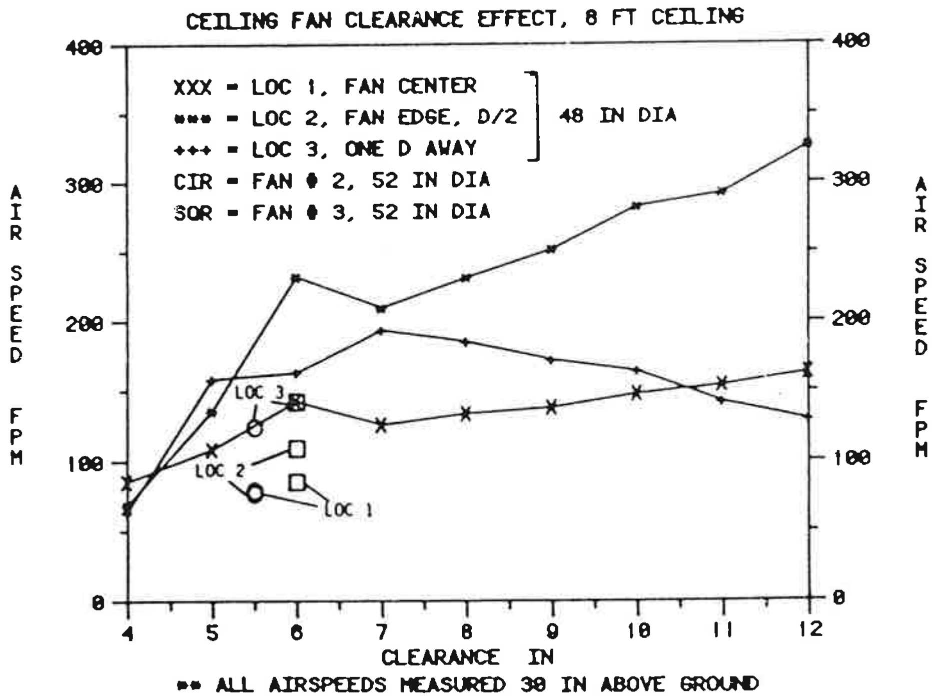

Figure 8. Airspeeds from ceiling fans as a function of clearance from ceiling

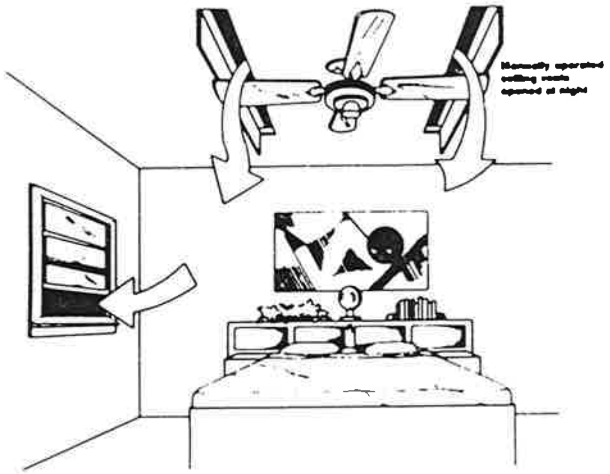

Figure 9. Attic-coupled ceiling fan for nighttime cooling