CHARACTERIZATION OF WIND-INDUCED PRESSURE DIFFERENTIALS AS DRIVING FORCES AFFECT INDOOR RADON ENTRY AND REMOVAL

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ABSTRACT

Wind-induced pressure differentials acting on a structure shell may affect both radon entry into the structure and indoor radon removal from the structure depending on the wind speed, direction, frequency, wave span, and structure features. Wind blowing directly toward a side of a structure may cause an increase in pressure at the structure wall in order to conserve the change in the momentum initiated by the change of wind velocity from the free stream area to almost zero at the wall side. A mechanistic model has been developed to predict pressure differentials generated in response to different configurations of wind movements around a structure. Parametric analysis has been performed to characterize pressure differentials generated from different wind configurations. The effect of wind-induced pressure differentials on indoor radon entry and removal were characterized using general approach to entry and ventilation modeling and applied using constant values exhibited by the University of Florida Radon Research House. The model and approach developed in this application can be used to quantify an acceptable range of wind conditions in which short-term indoor radon testing should be performed.

INTRODUCTION

The most significant convective component of radon transport from sub-structure area into the interior, and from the interior into the outdoors, is due to the pressure-driven air flow processes. Mechanisms which generate pressure gradients depend on environmental and indoor operational factors. The environmental factors that induce pressure differences include temperature differences, wind, meteorological conditions, and atmospheric pressure changes. The indoor operational factors can be divided into two parts: the human- and nonhuman-induced indoor operational factors. The nonhuman factors result from mechanically-induced pressurization or depressurization of the indoor environment by household appliances, as well as heating, ventilation, and air conditioning (HVAC) systems. Other cases can be represented by the human-induced indoor operational factors, which are characterized by effects such as opening windows and doors (Al-Ahmady 1995).

Wind blowing directly toward a side of a structure may cause an increase in pressure at the structure's wall in order to conserve the change in the momentum initiated by the change of the wind velocity from the free stream to almost zero at the wall, neglecting the effect of the ground. However, wind-induced pressure differentials usually fluctuate rapidly and the determination of the fluctuation frequency has been considered an important parameter (Nazaroff et al. 1988). Van der Hoven (1957) utilized Fourier transform analysis to obtain the frequency distribution of wind speed for a 100 m range. Fukuda (1955) had developed a theoretical treatment to obtain the wind-induced pressure frequency when such pressures are much smaller than atmospheric pressure.

The general scheme of characterizing the wind-induced pressures on radon entry can be connected to the soil permeability, the frequency of the developed pressure, and the magnitude of the developed pressure differential. More effects are expected to be observed when the frequency of the wind-induced pressure wave is long enough to propagate in the soil and large enough to produce a differential pressure across the structure slab and envelope. The indoor operational factor pressure generating mechanisms have been investigated by researchers using both experimental and mathematical models. These factors are more difficult to address since they include the effects of the occupants. The irregular opening of windows causes a decrease in the pressure difference, as well as an increase in the infiltration air.

In this paper, a mechanistic model to predict wind-induced pressure differentials across the structure shell was developed. Characterization of these pressure differentials on radon entry and removal rates were evaluated by integrating the model into basic mathematical representations of indoor radon entry and removal. Predictions for an actual structure were developed by using constants' values for the model based on measurements previously conducted at the University of Florida Radon Research House (UFRRH).

MODEL DEVELOPMENT

Starting from the physics of a fluid in motion, in this case air, the fundamental equation for conservation of fluid energy can be utilized to establish a correlation between wind speed and pressure. In this application, wind is assumed to be represented by an incompressible stream of air that has a Reynolds number much greater than one. Such conditions for this case are always satisfied.

Neglecting the shear stress between the wind stream and the ground surface, the conservation of energy (Bernoulli's equation) indicates that the total air energy under steady-state conditions must be constant at any point in the stream, therefore

$$1/2\ \rho\ v^2 + h\ \rho\ g + P = \text{constant} \qquad (1)$$

where P is the air pressure in Pa, h is the height of the point in meters relative to a horizontal reference, ρ is the air density (kg/m^3), g is the acceleration constant due to gravity (m/s^2), and
v is the air speed (m/s).

If the above equation is applied for two points in the air system, one point in the air stream around the structure when the pressure is not affected yet by the existence of the flow obstruction, and the other point at the surface of the structure wall, then

$$(0.5\ \rho\ v^2)_1 + (h\ \rho\ g)_1 + P_1 = (0.5\ \rho\ v^2)_2 + (h\ \rho\ g)_2 + P_2 \qquad (2)$$

For the height encountered in single family residential structures and short structures measured from the ground surface around the structure, the difference between the two quantities $(h\ \rho\ g)_1$ and $(h\ \rho\ g)_2$ is small enough to be neglected. Then Equation 2 can be written as,

$$P_1 - P_2 = \Delta P = 0.5\ \rho\ (v^2{}_2 - v^2{}_1) \qquad (3)$$

When the wind blows on the structure wall, its speed can be reasonably assumed to be zero at the surface of the wall. Therefore, if point 1 is selected to represent the area on the wall, the above equation reduces to,

$$\Delta P = 0.5\ \rho\ v^2 \qquad (4)$$

where v is the directional velocity of the wind stream measured by the weather station, and ΔP is the pressure difference between the wall outer surface and the pressure of the wind stream surrounding the structure. The wind stream pressure can be reasonably represented by the atmospheric pressure measured at the site, therefore the immediate pressure on the wall will be equal to,

$$P_{wall}(t) = P_b\ (t) + 0.5\ \rho\ v^2(t) \qquad (5)$$

The wind-induced differential pressure across the structure may then be calculated from,

$$\Delta P_w = P_{in} - P_{wall} = P_{in} - (P_b + 0.5\,\rho\,v^2) \tag{6}$$

MODEL PREDICTIONS AND DISCUSSION

Assumptions made during the preceding derivation neglect the effect of shear stress between the wind stream and the ground, the compressibility of air (particularly at the wall surface), and other factors that contribute to reduce the value of the pressure difference estimated by Equation 6. Therefore, this equation represents the maximum pressure difference that can be induced from wind blowing on the structure for the specific configuration. To account for the effects of the neglected factors, a constant, C_w (pressure or drag coefficient) is introduced into the equation that has a theoretical value ranging from zero to one.

The value of C_w is usually empirically determined through wind tunnel experimentation and is highly dependent on the particular cases of structure/wind configurations. Equation 6 is then written as,

$$\Delta P_w = C_w\,[P_{in} - P_b - 0.5\,\rho\,v^2] \tag{7}$$

Figures 1, 2, and 3 illustrate the model predictions of wind-induced pressure differences developed across the wall of a structure when the indoor pressure is constant and equal to the barometric pressure. The wind is blowing with a range of speed (from 0 to 25 m/s) with wind drag coefficients of 0.56 (windward side wall), 0.49 (side wall), and -0.15 (leeward side wall), respectively. Figure 4 illustrates the model predictions for wind-induced pressure differences across the structure shell for wind speeds of 1, 3, 5, and 10 m/s, and the full range of drag coefficients. As seen from the graphs, the drag coefficient has a negligible effect for the small range of wind speeds. Figures 5 and 6 illustrate the model prediction of wind-induced pressure differences generated in response to temporal variations in barometric pressure and indoor pressure equal to the time-averaged value of the barometric pressure for 1 and 14 m/s wind on the windward side wall and the leeward side wall of the structure, respectively.

To characterize the effect of pressure differentials generated by winds across the structure, indoor radon ventilation and entry rates need to be considered. The effects of natural and forced ventilation air on indoor radon concentrations can be generally attributed to the dilution of indoor radon through mixing with the ambient air which has a much lower radon concentration. Once the steady state radon concentration in the indoor environment reaches a high level, reduction of this concentration by ventilation is the only effective radon removal mechanism that can be employed. Ventilation forced by pressure differences between the indoors and outdoors needs to be employed to cause air change rates that dilute the elevated indoor radon concentration.

For the scope of this application, representation of structure variation rate can be quantified by the utilization of a blower door test, following the standard blower door testing protocols (ASTM 1987). This technique provides accurate measurements of indoor/outdoor differential pressures and the corresponding ventilation rates over the range of 2 to 50 Pa. The relationship between the structure ventilation expressed by the air volumetric flow rate across the shell, and pressure differentials can be written as,

$$Q = K\,(\Delta P_{shell})^n \tag{8}$$

where Q is the volumetric ventilation (or leakage) flow rate into or out of the structure in (m^3/s), ΔP_{shell} is the pressure differential across the structure shell in (Pa), n is the flow exponent and has a value between 0.5 and 1, and K is the flow coefficient for the structure in ($m^3/Pa^n.s$). Incorporating the wind-induced pressure differential model into Equation 8 yields,

$$Q = K\,[C_w\,(P_{in} - P_b - 0.5\,\rho\,v^2)]^n \tag{9}$$

Equation 9 can then be used to predict wind effects on structure ventilation and, consequently, indoor radon removal rate from structures. The values of K and n are empirically determined by the best linear regression. For the UFRRH, the flow coefficient was 0.0566 ± 0.0006, and the flow exponent was found to be equal to 0.69 ± 0.04. Figures 7, 8, and 9 illustrate predictions of different winds configurations on indoor radon removal rates using the above constant values.

Determination of the generic radon convective entry from the substructure area into the indoor can be determined by computing the correlation between simultaneous monitoring of indoor radon concentration and pressure differentials across the slab for a period of time. Experimental observations suggest that high linear correlation exists between the pressure differentials across the structure and the radon entry rate (Al-Ahmady 1995). The latter can be expressed as,

$$R_{conv} = B\,(\Delta P_{slab}) \tag{10}$$

where R_{conv} is the convective flow of soil gas-radon into the structure in Bq/s, and B is the correlation constant (Bq/s.pa) empirically determined for a specific structure. To evaluate wind-induced pressure differentials across the slab, a proportional coefficient needs to be applied to relate pressure difference across the structure shell to pressure difference across the slab as the following,

$$\Delta P_{slab} = B_w\,(\Delta P_{shell}) \tag{11}$$

and

$$R_{conv} = B\,[B_w\,C_w\,(P_{in} - P_b - 0.5\,\rho\,v^2)] \tag{12}$$

where B_w is the proportional constant between pressure differences across the slab and across the shell. This constant is equal to 1 when barometric pressure is constant over a period of time greater than the time needed by the sub-slab air volume pressure to equalize with the change in barometric pressure due to the damping response of the soil system (Al-Ahmady 1995).

The value of the constant B can be computed from a least square fit to differential pressure across the structure slab and indoor radon concentration measurement. For the UFRRH this value was computed as 13.23 (Hintenlang and Al-Ahmady 1994). Figure 10 illustrates predictions of wind-induced pressure differentials across the slab on the convective radon entry rate. It should be noted that these pressure differences depend on complexity interacting parameters including slab/foundation joints, soil characteristics, and wind characteristics. For practical concerns, the influence of wind-induced pressure differentials generated from wind movement around the structure on indoor radon entry is minimal when compared with their influence on the indoor radon removal rate.

CONCLUSIONS

Pressure differentials affecting radon entry from the substructure area into the indoor and indoor radon removal from the indoor to the outdoor, that generated from wind movements around the structure are interacting with many parameters including: wind speed and direction, wind wave fluctuation and span, structure shell and foundation details, and soil characteristics. A mathematical approach based on the conservation of wind momentum between wind stream and the structure shell, neglecting the share stress with the ground, can be used to develop a mechanistic model predicting pressure differentials generated in response to different wind/structure configurations. These wind-induced pressure differentials may then be integrated into mathematical representations of the structure ventilation and radon entry to characterize winds effects on radon removal and entry rates. It has been observed that wind-induced pressure differentials generated from different wind configurations have a minimal effect of soil-gas radon transport from substructure area into the interior when compared with their effects on structure ventilation and, consequently, indoor radon removal rates. The mathematical approach and model developed in this work may be used to quantify wind conditions upon which minimal effects are anticipated for the purpose of short-term indoor radon concentration testing.

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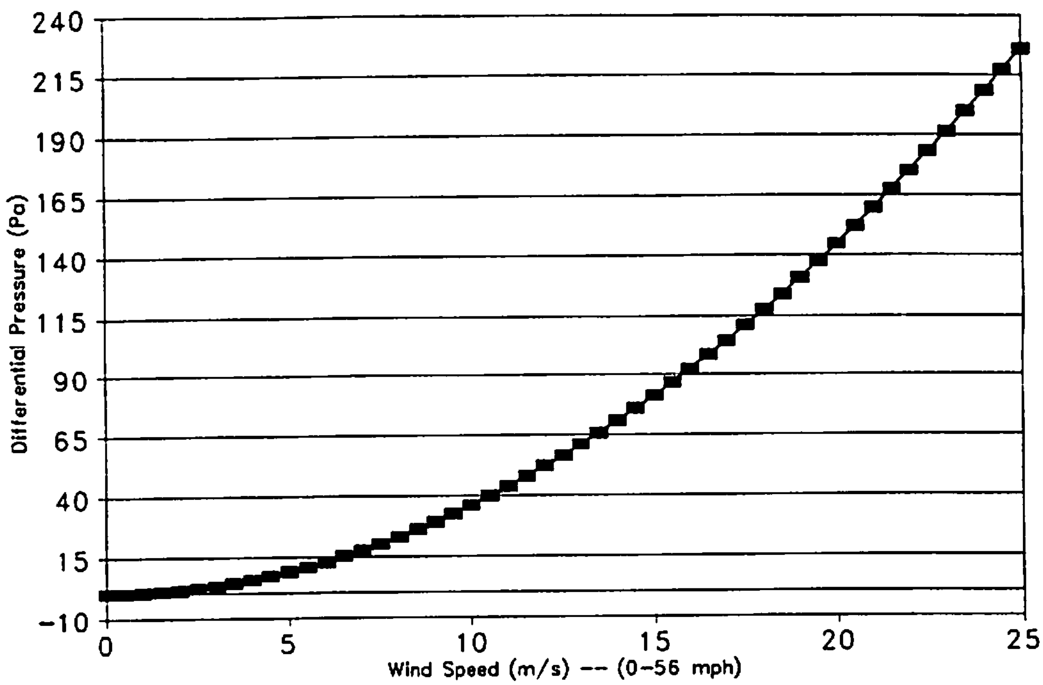

Figure 1: The wind-induced pressure differential predictions for a range of wind speed blowing on the windward side wall of a structure when the indoor pressure equals the barometric pressure.

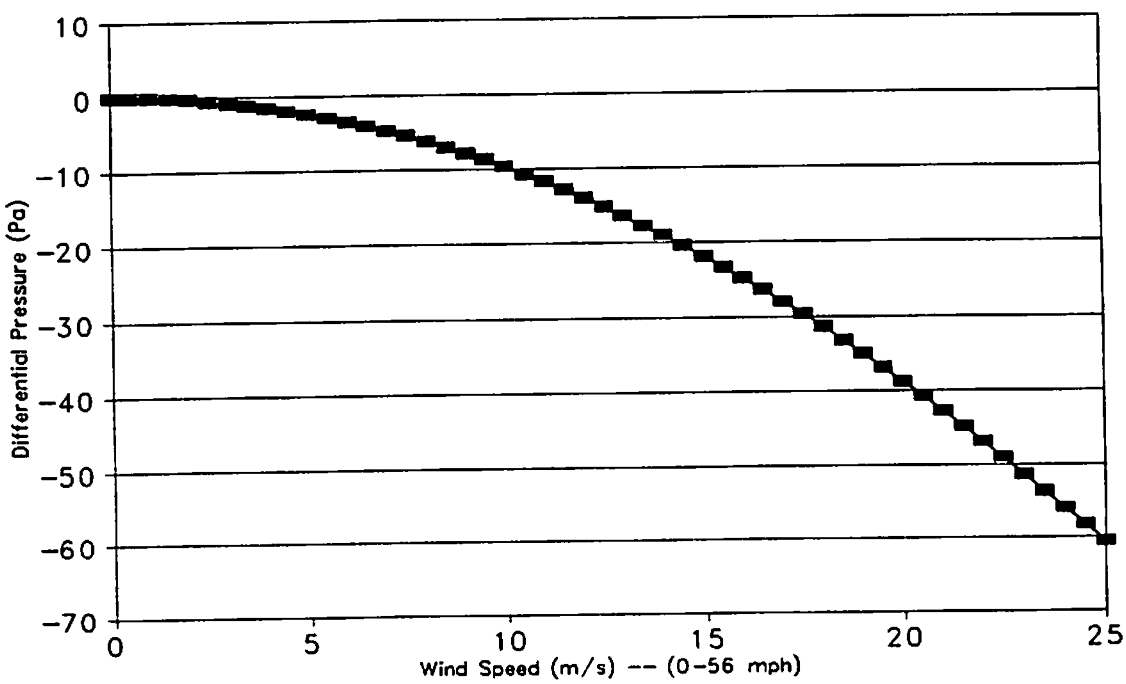

Figure 2: The wind-induced pressure differential predictions for a range of wind speed blowing on the leeward side wall of a structure when the indoor pressure equals the barometric pressure.

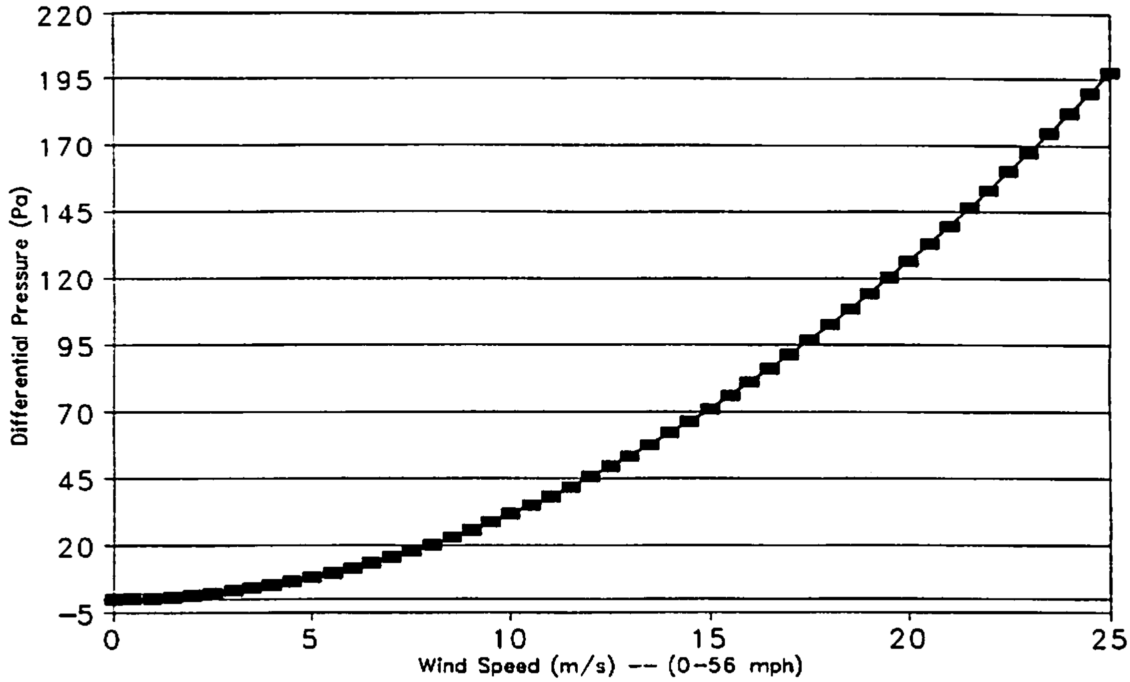

Figure 3: The wind-induced pressure differential predictions for a range of wind speed blowing on the side wall of a structure when the indoor pressure equals the barometric pressure.

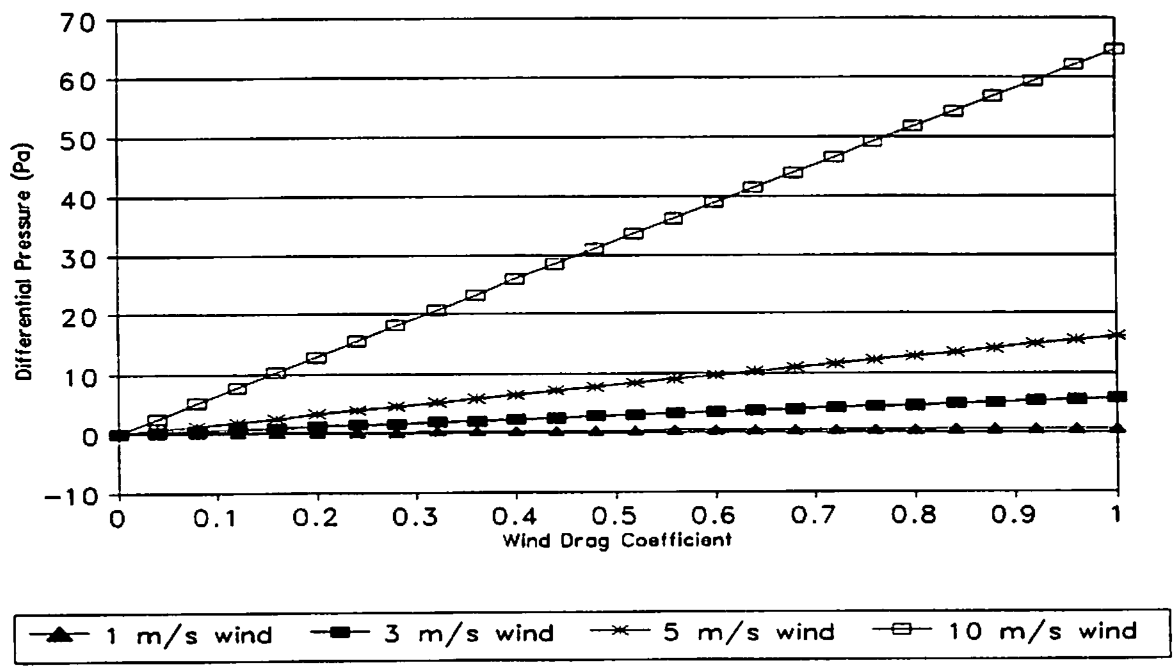

Figure 4: The model predictions of wind-induced pressure differences generated for several wind speeds blowing on the windward side wall of a structure as a function of the wind drag coefficient.

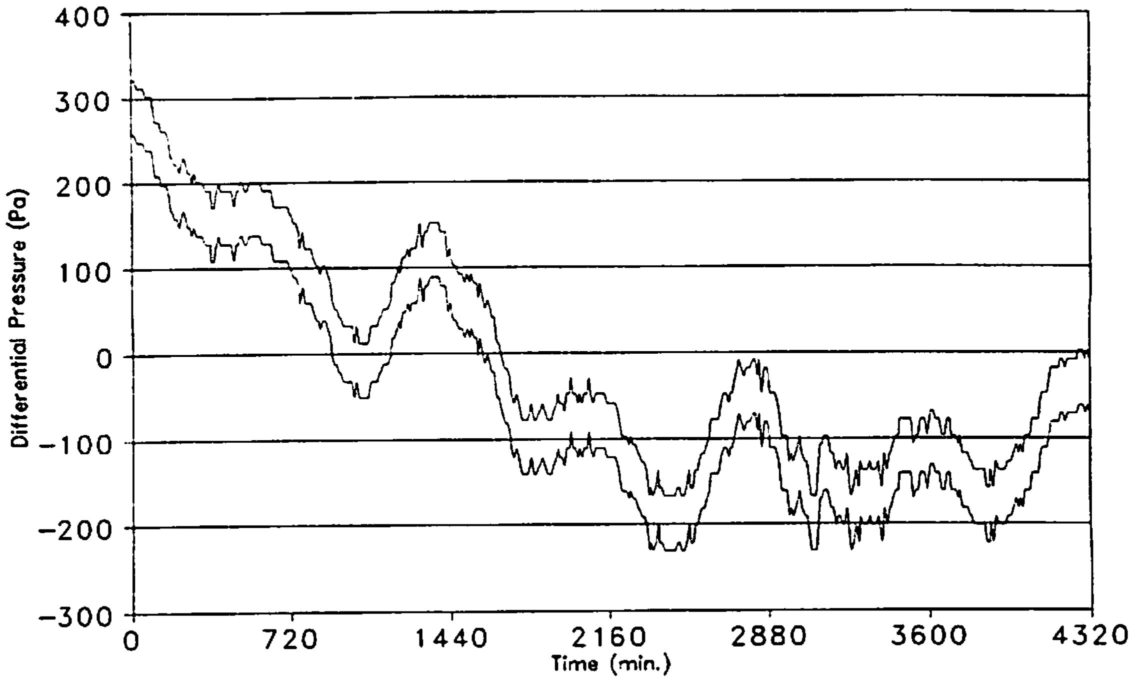

Figure 5: Prediction of wind-induced pressure differences in response to temporal variations in barometric pressure and indoor pressure equal to the average barometric pressure for 1 (lower curve) and 14 m/s wind on the windward wall.

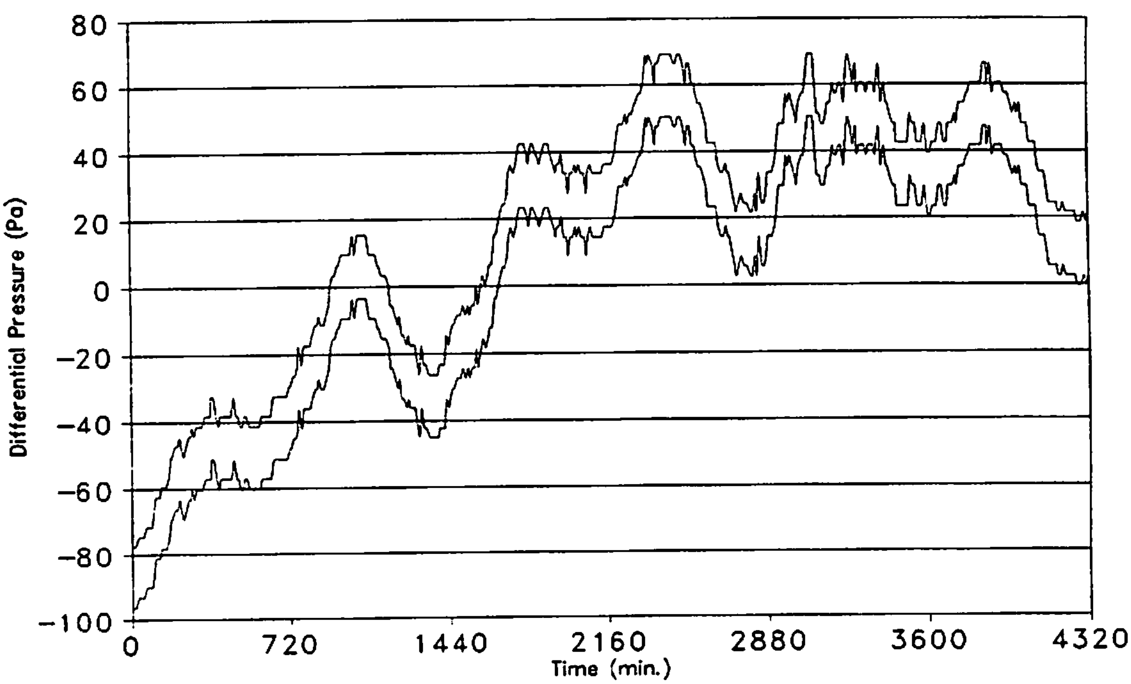

Figure 6: Prediction of wind-induced pressure differences in response to temporal variations in barometric pressure and indoor pressure equal to the average barometric pressure for 1 (upper curve) and 14 m/s wind on the leeward wall.

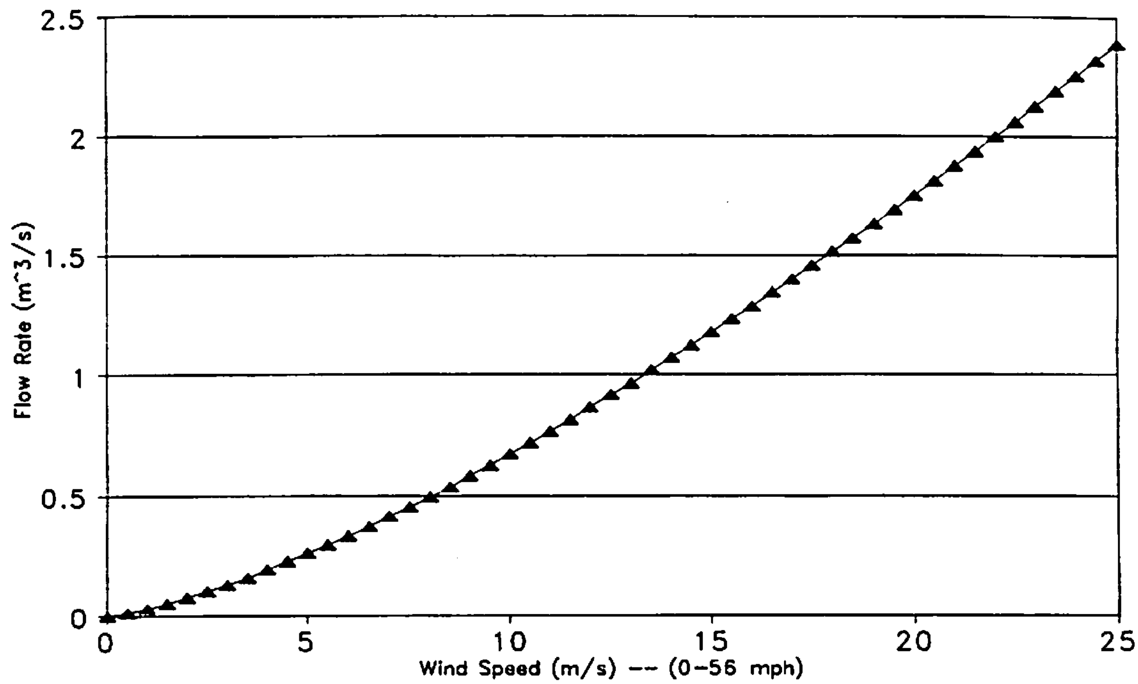

Figure 7: Predictions of the wind-induced pressure differential effects on the UFRRH ventilation for a range of wind speed blowing on the windward wall of the structure.

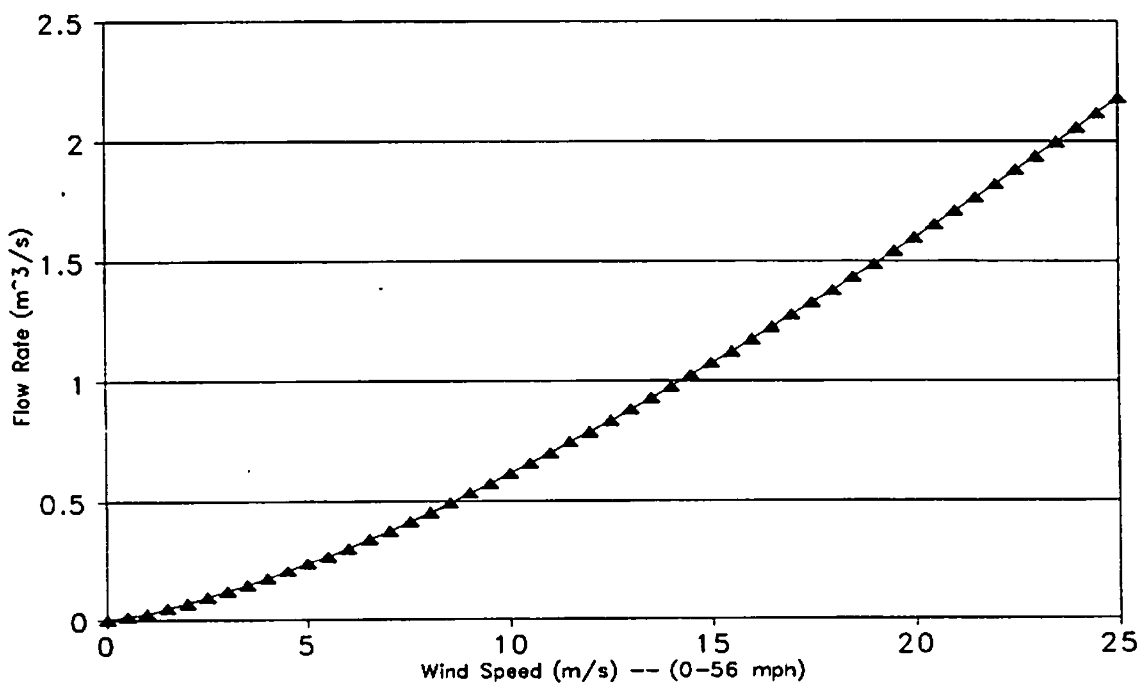

Figure 8: Predictions of the wind-induced pressure differentials effect on the UFRRH ventilation for a range of wind speed blowing on the side wall of the structure.

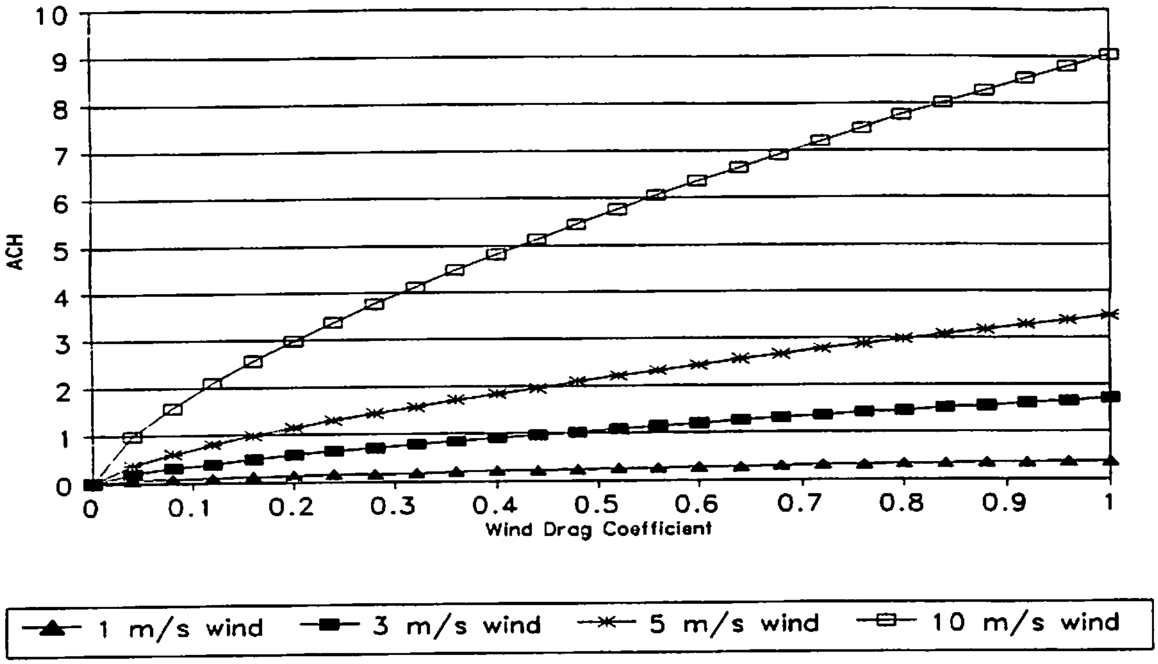

Figure 9: Predictions of the effect of wind speed on the UFRRH ventilation for all the possible interaction configurations developed by the wind direction and fluctuations across the structure.

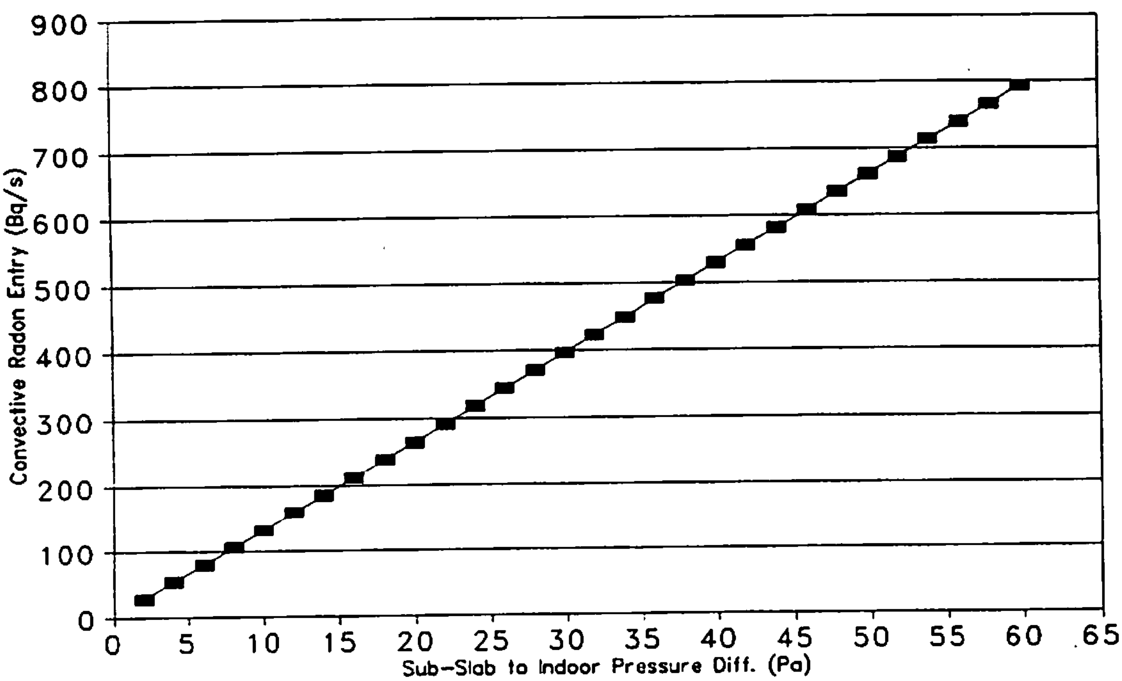

Figure 10: Predictions of the convective radon entry rate from the sub-structure area into the indoor for interior depressurization of 2 to 60 Pa.