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Natural Ventilation and Indoor Air Quality

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ABSTRACT

Natural ventilation has a long history of use to control thermal comfort. Ventilation research during the past two decades has concentrated on infiltration and mechanical ventilation. Recent work in studying natural ventilation is moving the design problem of predicting the performance of a natural ventilation system to a quantifiable basis. Natural ventilation is also receiving attention as a control strategy for indoor pollutants. This paper examines recent work that studies the use of natural ventilation for general indoor air quality control and its use as a solution for radon problems in buildings.

KEYWORDS

Natural Ventilation, Indoor Air Quality Control, Radon

INTRODUCTION

This paper is an examination of natural ventilation as a control strategy for air pollution within buildings. Let us first set the stage for the discussion. Research devoted to air pollution within buildings has been pursued vigorously for the past twenty years. These efforts have yielded significant understanding of the characteristics of air quality in buildings. Results are summarized with the following statements:

Air Pollution is a Buildings Problem.

If one examines air pollution from a public health perspective one asks where the primary exposure to air pollutants occurs. Since (1) pollutant concentrations are often as high or higher indoors than outdoors, and (2) the largest fraction of each person's day is spent within buildings, we conclude that the primary exposure to air pollutants (for non-smokers) occurs within buildings.

Indoor Air Quality Problems in Buildings Are Related to Sources.

Field measurements relating pollutant concentrations and ventilation rates have been made for many pollutants. In general there is no pattern showing low pollutant concentrations when ventilation rates are high and vice versa. Pollutant concentrations can be high in buildings with high or low ventilation; can be low in buildings with high or low ventilation. Comparing the ranges of variations seen indicate that concentrations often vary by larger factors than ventilation. Thus source strengths are at least as important as ventilation rates in determining concentrations in a building.

Ventilation Is the Best General Strategy to Control Air Quality Problems in Buildings.

This statement does not contradict the previous assertion. When pollutants and their sources are known to be present, source control must be employed to assure good air quality in the building. Ventilation works well for all pollutants, known and unknown. A prudent policy for general indoor pollutant control requires both control of excessive sources and the supply of adequate ventilation.

NATURAL VENTILATION AS AN INDOOR AIR QUALITY CONTROL TECHNIQUE

We shall use ASHRAE terminology to distinguish natural ventilation (i.e., flow through intentional openings caused by pressures from wind and indoor-outdoor temperature differences) from infiltration (the uncontrolled flow of air through unintentional openings driven by wind, temperature difference, and appliance-induced pressures [ASHRAE, 1989a]).

Extensive research in infiltration has led to the development of single zone models for buildings; multi-chamber flow models are now part of the research repertoire of many research groups (Feustel, 1990). Distribution of ventilation air flows in mechanically ventilated spaces continues to receive significant attention (Fisk et al., 1991; Persily and Dols, 1991; Kato and Murakami, 1988). By contrast, natural ventilation has received little notice from the engineering community. Note, for example, the list of qualitative "rules-of-thumb" for natural ventilation in the ASHRAE handbook of fundamentals (ASHRAE, 1989a). This ventilation strategy has long been a favorite of architects who draw arrows showing flows into and out of spaces. It is now beginning to receive the research attention (in some cases from architects) that will allow the arrows to be quantified and be used to predict heat transfer and the ability to remove pollutants (Ernest et al., 1991; Murakami et al., 1991).

The history of natural ventilation extends back for centuries. Vitruvius describes the comfort control system for public Roman bath's by noting (quoted in Lord, 1986)

> ... an aperture left in the middle of the dome with a bronze disc hanging from it by chains. By raising and lowering the disc, the temperature ... can be regulated.

Several ventilation strategies exist for indoor air quality control. The most effective is task ventilation, i.e., ventilation of a pollutant source directly to the outside. This technique, which is a form of source control, prevents the pollutant from spreading throughout the building which would require subsequent dilution of all the air in the building to remove the pollutant. Examples include direct exhaust ventilation above cooking surfaces, and direct exhaust ventilation of rooms containing office equipment such as copy machines. Sub-slab ventilation for radon control, described below, is another example of task ventilation.

Whole building ventilation provides oxygen to building occupants and removes pollutants generated by these same occupants and other sources in the building. In many countries it also provides the thermal comfort control for the space, an activity that occasionally conflicts with IAQ control requirements.

MATHEMATICAL DESCRIPTION OF NATURAL VENTILATION

It is useful to think of natural ventilation as a two-step process. Flow through an inlet opening occurs due to a pressure difference between the air mass at the inlet and the pressure within the building. Using the notation of Wilson and Walker (1991) the flow through an inlet of area A_{inlet} is given by Bernoulli's equation

$$Q_{inlet} = C_d \, A_{inlet} [\, 2 \, (\, P_{inlet} - P_{indoor} \,) / \, \rho_o \,]^{0.5} \tag{1}$$

where
Q_{inlet} is the flow through the inlet
C_d is the discharge coefficient of the inlet
A_{inlet} is the physical area of the inlet
P_{inlet} is the pressure of the outdoor air mass at the inlet
P_{indoor} is the pressure in the indoor space, and
ρ_o is the density of the outdoor air

Similarly the flow through the outlet is given by

$$Q_{outlet} = C_d \, A_{outlet} \, [\, 2 \, (\, P_{indoor} - P_{outlet} \,) / \, \rho_i \,]^{0.5} \tag{2}$$

where
Q_{outlet} is the flow through the outlet
C_d is the discharge coefficient of the outlet
A_{outlet} is the physical area of the outlet
P_{outlet} is the pressure of the outdoor air mass at the outlet
P_{indoor} is the pressure in the indoor space, and
ρ_i is the density of the indoor air.

The pressure in the indoor space, P_{indoor}, adjusts to satisfy the conservation condition

$$Q_{inlet} = Q_{outlet}. \quad (3)$$

If we assume

$$\rho_i = \rho_o \quad (4)$$

(at most a 5% error in flow unless dealing with extreme conditions) and using the symbol **r** to represent the ratio between inlet and outlet areas we obtain

$$Q = C_d \, A_{outlet} \, [(2r^2/(1+r^2))((P_{inlet} - P_{outlet})/\rho)]^{0.5} \quad (5)$$

where Q_{outlet} is the flow through the outlet
C_d is the discharge coefficient of the outlet
A_{outlet} is the physical area of the outlet
P_{outlet} is the pressure of the outdoor air mass at the outlet
P_{indoor} is the pressure in the indoor space, and
ρ is the density of the indoor air.

There is a symmetry to the flow described by this expression. When **r** is small the flow is linearly proportional to the size of the inlet area and thus is controlled at the inlet. When the areas are equal the pressure within the building is the average of the inlet and outlet pressures. When **r** becomes large the flow is linearly proportional to the outlet area and is controlled at the outlet.

It is important to note the limitations of this simplified treatment. Murakami et al.(1991) have pointed out that in conditions of large cross-ventilation flow, virtual stream tubes are formed and kinetic energy in the flow is preserved after passing through the windward and leeward openings. The appropriate mathematical treatment in this case is a three-dimensional numerical simulation using the Navier-Stokes equations.

Sources of Pressure Differences

The pressure differences that enter the expressions above come from two primary sources, the wind and indoor-outdoor temperature differences, sometimes called the stack effect. The wind pressure is troublesome because of its directional character and because of the variation in wind speeds over the course of a year. This variability forces a designer to arrange ventilation openings on all sides of the structure if there is no prevailing wind direction. It also forces the use of large openings to allow adequate flow when the pressure differences are small.

The stack pressure depends on the indoor-outdoor temperature difference and the height of the structure. It can be a major cause of flow during the winter when indoor-outdoor temperature differences are large; it is a weak pressure source during the other three seasons when attempts are made to use it for night cooling and air quality control.

EXPERIMENTAL TESTS OF THE PERFORMANCE OF NATURAL VENTILATION SYSTEMS

Much of the design interest in natural ventilation arises from a desire to supplement or replace mechanical cooling rather than to provide indoor pollution control. Ventilation cooling occurs in at least three ways,

1. cool outdoor air can reduce the effects of internal and solar gains;

2. natural airflow can cool a structure reducing the radiant temperatures an occupant experiences; or

3. air motion increases the cooling of occupants.

A recent study reported by Ernst, Bauman and Arens (1991) describe an empirical model they have developed for predicting wind-induced indoor air motion in naturally ventilated buildings. The model resulted from boundary layer wind tunnel measurements on architectural models. Two sets of tests were used. The first consisted of measurements of air speed and turbulence intensity in models having various opening configurations. The second group were measurements of external surface pressure distributions of models having the same configuration. Results are presented in the form of equations correlating the velocity coefficient, the wind direction, the pressure coefficient of the upwind opening, the pressure coefficient of the downwind opening and the difference of the pressure coefficients.

Murakami et al. (1991) measured flows and pressures in wind tunnel models to examine cross-ventilation flow patterns. Their work points to the need to describe these flows using three-dimensional flow equations rather than the simplified treatment based on Bernoulli's equation described above.

Results from both studies beg for field verification. In particular, the limitations of the validity of the simplified treatment should be determined. Both studies represent important steps in developing our ability to predict natural ventilation airflows from wind parameters.

Stack Cooling

Van der Maas and Roulet (1991) examined the potential for night-time cooling in naturally ventilated spaces. High mass buildings reduce temperature swings in indoor spaces. These large temperature swings can be an effective tool for nighttime cooling of the interior spaces in buildings. The authors developed a model that predicts total heat extracted from a building at night and verified it in experimental studies of a high mass staircase in a three story laboratory facility. Their model presents design guidelines for opening sizes, wall surface area and wall thermal properties so that designers can estimate the effectiveness of ventilation cooling for a particular climate.

APPLICATIONS TO INDOOR AIR QUALITY CONTROL

Two basic kinds of studies have been undertaken using natural ventilation for indoor air quality control. The first begins with the premise that adequate air quality will be achieved if the ventilation rates of some appropriate standard such as ASHRAE 62-1989, Ventilation for Acceptable Indoor Air Quality, occur in a building (ASHRAE, 1989b). Natural ventilation is explored as an appropriate strategy to use to provide these ventilation amounts. A second control strategy attempts to reduce a pollutant concentration to some predetermined value by adding ventilation supplied using the principles of natural ventilation. The papers of Wilson and Walker (1991) uses the former approach; the work of Saum and Osborne (1990), Brennan et al. (1990), and Saum (1991) use the latter.

General Results

A major study of the effectiveness of natural ventilation to supply appropriate ventilation air to small structures (residences) has recently been reported by Wilson and Walker (1991). Their study examined five different full scale housing configurations in a controlled, long-term laboratory situation in Edmonton, Alberta. (CANADA). The goal of their study was to examine whether one of five variations of natural ventilation opening configurations would provide ventilation quantities adequate to meet the ventilation requirements for residences in ASHRAE 62-89. Their extensive study, over a three-year period, with continuous logging of meteorological data and natural ventilation rates concluded that natural ventilation would not provide adequate ventilation air to the space throughout the year.

Generalizing from their results, that are applicable to detached houses and town-houses in a cold climate, Wilson and Walker argue that

1. adequate ventilation for detached houses in winter requires no design natural ventilation openings. Infiltration driven by a large stack effect is a sufficient source of ventilation. The same is not true for attached town houses with only two exposed walls.

2. Large openings are required for adequate natural ventilation in spring, summer, and autumn. These lead to severe over-ventilation in the winter.

3. Inlet damper control that responds to temperature differences <u>and</u> to the wind will be required if adequate

ventilation throughout the year is to be provided in cold climates.

Radon Mitigation

Radon is a major indoor air pollutant, present in buildings worldwide. Its major source is the soil; its primary entry mechanism is the pressure difference between the soil gas containing the radon and the interior of buildings(Nero and Nazaroff, 1988). Mitigation techniques have been developed that deplete the radon concentrations in contact with the substructure of buildings and also reduce the pressure difference driving the flow into buildings. The most common mitigation system involves a technique known as sub-slab ventilation. A standard configuration for a sub-slab ventilation system in a residence consists of a vertical pipe that extends from beneath the floor of the basement to an exhaust in the atmosphere above the roof. The pressure difference required for the flow through the pipe is produced by an in-line fan that operates continuously. The standard fan recommended by the EPA is sized to produce a flow of 50 m^3/hr and uses 640 kWh per year (Bohac et al., 1991).

Passive Stacks

The possibility of using passive stacks, i.e., a vertical pipe that does not contain an axial fan, to accomplish the same mitigation has been investigated by Saum and Osborne (1990), and Brennan et al. (1990). Results of their work have been revised and are presented in the paper of Saum (1991) described below. Figure 1, produced from data in the latter paper, illustrates the reductions in concentrations obtained using passive stacks. The reductions in concentrations average approximately 70% of the unmitigated values.

If fans are used in the stacks, the reductions average 98%. From the perspective of an individual who is concerned about radon it is clear that the stack with a fan is a far better solution to the radon problem than a passive stack. The energy penalty from operating the fan continuously for a year in a cold climate is the order of $80 annually (Bohac et al., 1991). The change in exposure caused by the active system is 40% greater than the change caused by the passive system. On the other hand, from a public health policy perspective, if the reduction in cost of the passive stack increases the market penetration of the passive mitigation system by a factor of 1.4 times the penetration of the active system, the cumulative exposure to the public will be reduced by developing passive stacks as common features in new construction.

Minifan Supplements

An alternative has emerged to the passive stacks and the 80 watt fans in common use in mitigation. Saum (1991) has suggested that a 10 watt minifan, currently under development, could supplement the pressure produced by the stack effect and reduce the radon concentration substantially with only a modest increase in cost above the inexpensive passive stack. Concentrations using the minifan typically are reduced 98% in tests reported. This deserves further investigation in houses having different soil conditions and found in different climates. If the market accepts the strategy it will be a major improvement in public health.

CONCLUSION

Natural ventilation has begun to receive research attention as a strategy for inexpensive thermal comfort and as an indoor air quality control strategy. Recent results suggest that natural ventilation, of itself, is probably inappropriate as an indoor air quality control strategy. However, one is not forced to rely on pure natural ventilation to achieve adequate control. Natural ventilation supplemented by other technologies (damper controls or small fans) at appropriate times of the year can reduce or eliminate problems that have been observed. The energy savings can be considerable since ventilation costs can be a significant portion of a building's energy budget.

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FIGURE CAPTION

Figure 1. The open bars depict the average radon concentration in the houses tested when the passive stacks were closed and inoperative. The shaded bars illustrate the average concentrations when the stacks were opened. The percentage reduction for each case is shown above the bar. All data are one or more weeks of hourly readings from a continuous radon monitor. W and S on the house identifiers refer to Winter and Summer measurements. All radon control systems were installed by the builder without supervision of a radon control expert. The figure was prepared from data in the paper of Saum (1991).

Effect of Passive Stack on Radon Concentrations in Residences