SIMULATION OF THE PERFORMANCE OF TRICKLE VENTILATORS

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ABSTRACT

This paper presents the results of a simulation study regarding the potential of trickle ventilator integration in ventilation design of office buildings. Design solutions for the opening area of trickle ventilators to satisfy the fresh air requirements, as recommended by ASHRAE Standard 62, are presented. The results are compared with the BRE recommendations. It was found that trickle ventilators should be used with fan assistance (hybrid ventilation) in stack-dominated office buildings to ensure that the required flow is delivered, especially at the upper floors. The required opening area varies with the height location of the trickle ventilator and the outside temperature. However, assuming typical Montreal design conditions and occupancy less than 12 m^2 per person, the study found that at least 5 cm^2 opening area per m^2 of floor area is required to ensure an acceptable comfort level for occupants.

INTRODUCTION

In naturally-ventilated buildings, fresh air is provided through openings, and there is a wide range of possibilities regarding the selection of the opening type and the position in the façade. Different flow patterns are developed for various opening types and positions resulting in different values of ventilation capacity, controllability, impact on comfort and indoor air quality (IAQ) [1]. During the last two decades interesting new devices and controls have been developed while size and control of inlets have become vital elements in design.

Trickle ventilators are commonly used means to provide natural, background passive ventilation. These are manually operated air-inlets fitted to window openings (preferably at the top) to allow fresh, outside air passing through. The amount of air is usually sufficient to improve indoor air quality without significantly affecting the energy cost. A large variety of trickle ventilators exist but basically, can be classified into two categories: fixed and controlled (pressure, humidity, temperature or pollution) trickle ventilators; the latter are intended to provide a constant natural supply of air flow independent of wind - and temperature - induced pressures. Figure 1a shows the slot and Figure 1b the pressure-controlled ventilator considered in this study.

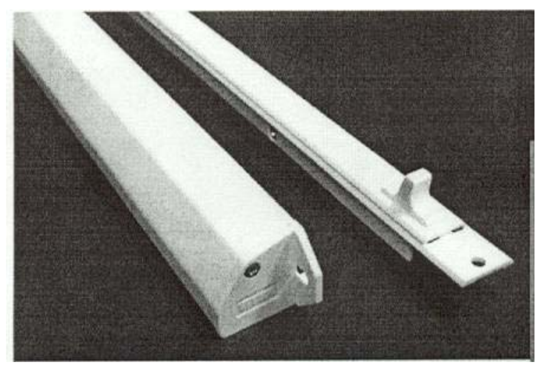

Figure 1(a). Slot ventilator.

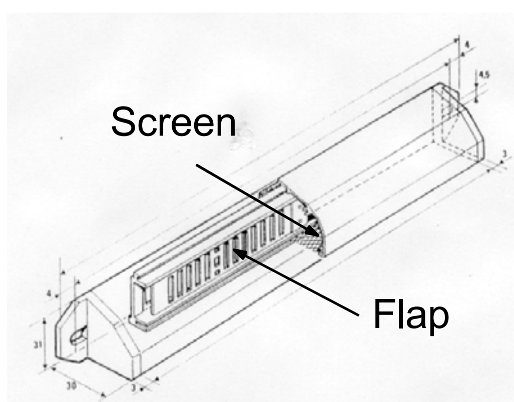

Figure 1(b). Pressure-controlled ventilator.

Trickle ventilators are widely used in European countries and have become part of many Building Standards such as those of BRE [2] and CIBSE [3]. However, this concept is relatively new in North America, and only during the last few years, trickle ventilators have been installed in several commercial buildings.

Trickle ventilators can be used in ventilation design of buildings as stand-alone systems utilizing only the natural driving mechanisms (wind and stack-induced pressure) or in conjunction with mechanical exhaust systems, i.e. hybrid ventilation [4]. Hybrid ventilation systems can be described as providing a comfortable internal environment using different features of both natural and mechanical ventilation systems at different times of the day or season of the year. The focus in the development of this type of ventilation system has been to reduce energy consumption while maintaining a comfortable and healthy indoor environment [5].

An experimental study including CO_2 and temperature monitoring [6] showed that trickle ventilators with a minimum openable area of 4 cm^2 per m^2 of floor area can provide adequate fresh air in a typical office room with maximum occupancy density of 8 m^2 floor area per person. However, these results [6] cannot be generalized because the experiments were carried out under specific climatic conditions (UK climate) and for a given building. An overview of the availability, performance and application of existing trickle ventilators (fixed and controllable) concludes that although these are promising systems in terms of indoor air quality, comfort and energy, their integration in ventilation design of buildings still requires a lot of investigation [4]. The leakage characteristics of the slot and pressure-controlled trickle ventilators considered have been determined experimentally in a field study [7]. In the same study, an investigation of the performance of trickle ventilators when the wind flow dominates was performed.

In this paper the potential of trickle (slot) ventilator integration in ventilation design of office buildings is investigated through a simple flow network model. Design solutions for the required opening area of trickle ventilators to satisfy the fresh air requirements, as recommended by ASHRAE Standard 62 [8], are presented. The performance of slot ventilators is simulated since fan depressurization test results [9] show that the air flow through slot ventilators is predictable for any pressure differential expected on the building envelope. Simulation of the performance of pressure-controlled ventilators is more complex due to the effect of the exterior flap (see Figure 1b) causing internal pressure variations, which are difficult to simulate. Furthermore, the opening area of the interior part (actual opening) is not the same with that of the flap, and more experimental research is required to measure the air flow through the pressure-controlled ventilator as a function of the ratio of the interior part and the flap opening area.

SIMULATION STUDY

The air flow through an opening, as a function of the pressure difference ΔP across it, may be expressed as:

$$Q = C \cdot (\Delta P)^n \qquad (1)$$

where C ($m^3/s/Pa^n$) is the flow coefficient and n (dimensionless) is the flow exponent of the opening. Therefore, the leakage characteristics of the slot ventilator are required for the development of the simulation flow network. As already mentioned, these were determined in [7] based on the ASTM E783 method [10] for an opening of 40 cm^2. According to the results of this study, the air flow through the slot ventilator, Q_s (m^3/s) can be described by:

$$Q_s = 0.0016 \cdot (\Delta P)^{0.53} \qquad (2)$$

in which the flow exponent (n = 0.53) for the slot ventilator indicates turbulent flow. Equation (2) is also in good agreement with data from CIBSE [3] suggesting a value of n of about 0.5 for trickle ventilators. A comparison of the field data with theoretical estimations of the air flow through slot ventilators based on the orifice equation with discharge coefficient (C_D) equal to 0.6 shows that the latter overestimates the air flow unless a value of C_D approximately equal to 0.34 is considered for application of the orifice equation in the case of trickle (slot) ventilators.

In the present study, a typical 4 m × 3 m × 4 m office space with a window is considered and the potential integration of trickle ventilators is investigated for different design parameters, i.e. exterior temperature, wind speed, pressure coefficient and opening height. Figure 2 shows a schematic of the simulated office. A slot ventilator, integrated in the upper part of the window frame at 3 m height from the floor, is considered as passive inlet to deliver fresh air inside the office. Exhaust grills, which are part of a low horsepower variable speed fan (exhaust part of the HVAC system) are considered as outlet. The fan may be considered when the natural driving mechanisms, wind and stack effect, are not adequate to drive the air flow (hybrid ventilation system).

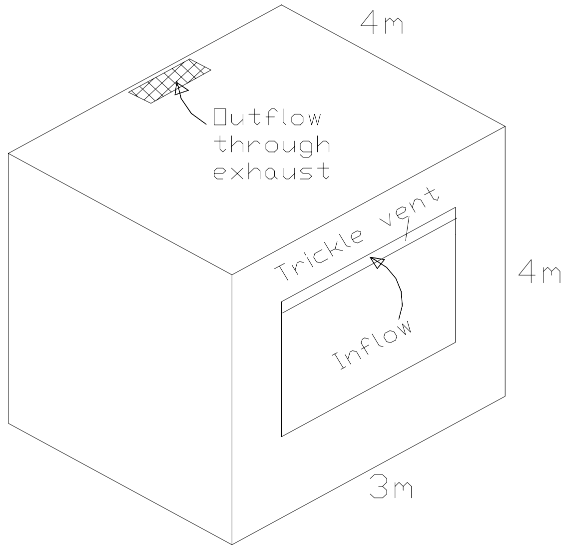

Figure 2. Schematic of the simulated office.

An algorithm has been developed using Mathcad 2001 Professional to calculate the opening area of the trickle ventilator based on the occupancy (or airflow requirements) and a specified (desirable) internal pressure for different design parameters. For the assumed occupancy, the ventilator should satisfy the fresh air requirements since it is the only inlet. The simulated office is assumed airtight and, therefore, the effect of the leakage is not considered. Based on the leakage characteristics of a 40 cm^2 slot ventilator [7], the flow coefficient per unit area is calculated and the wind and stack pressures are evaluated. By solving the mass balance equation, the required opening area of the trickle ventilator is calculated for different design parameters. For the case of other openings present, the air flow passing through should be considered in the mass balance equation.

Leakage characteristics

Equation (2) shows that the flow coefficient of a 40 cm^2 opening area slot ventilator is 0.0016 $m^3/s/Pa^{0.53}$ [7]. The flow coefficient of a ventilator with opening area A can be expressed as:

$$C = K \cdot A \tag{3}$$

where K is the flow coefficient per unit area which is equal to 0.4 ($m/s/Pa^{0.53}$). BRE Digest 399 [2] recommends 4 cm^2 opening area per m^2 of floor area to satisfy the fresh air requirements (maximum occupancy 8-10 m^2 per person). Thus, for the simulated office space, which has 12 m^2 floor area, 48 cm^2 of opening area is required. It is assumed that the flow exponent remains the same ($n = 0.53$) for such small variations in the opening area.

Stack pressure

During the heating period outside air enters the building at the lower floors while the warmer inside air rises and flows out of the building from the upper floors. The stack pressure, P_s (Pa) is given by the following equation:

$$P_s(T_o,h) = \rho \cdot g \cdot (H_{NPL} - h) \cdot \frac{T_i - T_o}{T_i} \tag{4}$$

where ρ is the air density, g the gravitational acceleration, T_i the inside temperature, T_o the outside temperature, H_{NPL} the Neutral Pressure Level (NPL) height, and h the opening height.

Wind pressure

For openings located on the windward side of the building, the air is forced into the building due to the existing positive wind pressure. For leeward openings the flow is directed from inside to the outside due to the existing negative pressures. The mean wind pressure, P_w (Pa) is given by the following equation:

$$P_w(V,C_{pe}) = \frac{1}{2} \cdot C_{Pe} \cdot \rho \cdot V^2 \tag{5}$$

where C_{pe} is the mean external pressure coefficient and V (m/s) the mean wind speed at the opening height.

Opening area calculation

The driving mechanisms of the building pressurization are predictable for specified wind direction and location on the building envelope (C_{pe}), outside temperature, wind speed and opening height (design parameters). The total stack and wind-induced pressure is given by:

$$P_t(T_o,h,V,C_{pe}) = P_s(T_o,h) + P_w(V,C_{pe}) \tag{6}$$

The outside-inside pressure difference may be expressed as:

$$\Delta P(T_0,h,V,C_{pe}) = P_s(T_o,h) + P_w(V,C_{pe}) - P_{in} \tag{7}$$

where P_s and P_w are given by equations (4) and (5) and P_{in} (Pa) is the internal pressure relative to the outside static pressure at the same height (input value). It is assumed that the internal pressure is kept constant at a pre-specified value. The required air flow is calculated based on the occupancy. According to ASHRAE Standard 62 [8], about 10 L/s per person of outside air should be supplied to satisfy the fresh air requirements. Therefore, the supply flow rate (m^3/s) may be expressed as:

$$Q = O . Q_{req} \tag{8}$$

where O is the occupancy (number of persons) and $Q_{req} = 0.01\ m^3/s$.

According to mass balance, the exhaust flow rate is equal to the supply flow rate. Therefore, the air flow exhausted through the fan (exhaust grills) will be equal to the air flow coming in through the ventilator. Since the ventilator is the only inlet opening, the airflow passing through should satisfy the fresh air requirements:

$$Q = C \cdot (\Delta P(T_0, h, V, C_{pe}))^n \quad (9)$$

where C and n are the leakage characteristics of the ventilator, Q the supply air flow rate calculated from equation (7), and ΔP (Pa) the inside-outside pressure differential. By substituting equations (3), (7) and (8) into (9) the required opening area (cm^2) is calculated:

$$A(T_o,h,V,C_{pe}) = \frac{O \cdot Q_{req}}{K \cdot (P_s(T_o,h) + P_w(V,C_{pe}) - P_{in})^n} \cdot 10^4 \quad (10)$$

CASE STUDY

The building and its design environment

A planned 17-storey, 68 m high building, which will be located in downtown Montreal is considered for the numerical simulations. Similar office spaces such as that described in the previous section are assumed on each floor in the windward façade of the building. Design conditions assume that natural ventilation can be used when the outside temperature is between 10° and 20°C and the relative humidity is less than 70%. When the outside conditions are not adequate to satisfy the design requirements, only mechanical ventilation is used. The building will not be exposed to extremely high wind speeds. The wind speed in Montreal typically varies between 0 and 10 m/s. The mean external pressure coefficient was assumed to vary between 0.2 and 0.8 [11] since only windward openings are considered.

Figure 3 shows the hybrid ventilation strategy planned. The system is designed to satisfy the fresh air requirements according to ASHRAE Standard 62 [8]. Slot ventilators with appropriate sizing are considered as passive inlets to deliver fresh air inside the building. A 68 m high exhaust chimney is considered with a low horsepower, variable speed fan (exhaust part of the HVAC system) installed on the top. The fan may be operational to locate the NPL on the top of the building and to provide the total exhaust required only when the natural driving mechanisms are not sufficient to drive the appropriate air flow (hybrid ventilation system). A chimney temperature T_i = 26°C is considered in equation (4) and the flow resistance between the room and the chimney as well as within the chimney is assumed to be negligible. These assumptions are not expected to

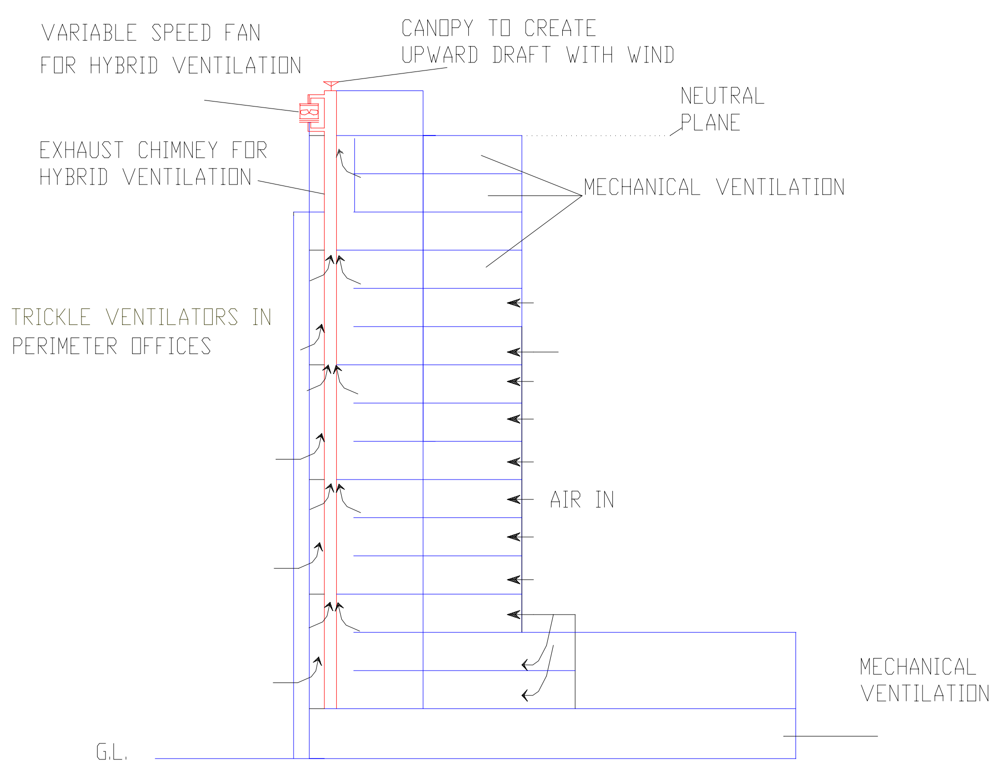

Figure 3. Hybrid ventilation strategy.

lead to uncertainty in assessments for design purposes because the fan operates to minimize the effect of these resistances and to avoid possible cross-contamination of the stream of air in the chimney in the case of back drafts into rooms on the top floors if the vents are not properly sized. Proper design of the chimney is required to avoid possible cross-contamination and insufficient exhaust flow for the case that the hybrid ventilation is shut off suddenly.

A variable air volume HVAC system (VAV) has been suggested for the conditioning of the indoor air. When the outside conditions are favorable, the trickle ventilators can be manually operated and the supply part of the HVAC system will be closed automatically by a damper. The exhaust part of the HVAC system (grills) is used continuously (as passive or active outlet) to exhaust the air coming in through the ventilator. When a sufficient amount of air can be delivered by the natural driving mechanisms, the grills are used as passive outlets; for insufficient flow of outside air inside the building, the fan exhausts air and thus the grills become active outlets. Dampers with pressure sensors may be installed in each office to ensure that the required flow is delivered and to keep the internal pressure at about –1 Pa. The dampers can be located either at every trickle ventilator or in the exhaust grills. Appropriate sizing of the trickle ventilators is essential in order to supply the required air flow rate, reduce the operation of the fan while maintaining a desirable internal pressure.

For a high-rise building the stack effect is expected to be the dominant driving force. Figure 4 shows the variation of the stack pressure with height for an outside temperature of 15°C evaluated by equation (4). Wet labs will be located between the 13th and 17th floor and, therefore, mechanical ventilation is required to achieve the appropriate pressure drop and isolate contaminant sources. Natural ventilation is assumed for the 2nd to the 13th floor of the building (slot ventilator height from 7 to 51 m). The first floor, which is near pollutant sources (e.g. cars, dust, nearby building exhaust systems, etc), is mechanically ventilated to restrict the polluted outside air from coming into the building. It is also assumed that this ventilation strategy is employed only in the perimeter zone of the building; the latter will be conditioned separately from the internal zones or spaces and, therefore, leakage between an office and the corridors is assumed to be minimal.

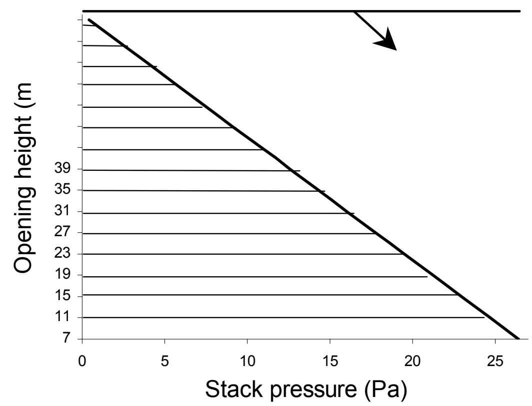

Figure 4. Stack pressure at the location of slot ventilators (T_o = 15°C).

Sensitivity analysis
A sensitivity analysis is carried out in order to establish the validation of the assumptions made in the previous section. Figures 5 shows the variation of the total pressure, which is calculated using equation (6), as a function of the wind speed at outside temperatures 10°, 15°, and 20°C; results are given for four individual heights of the trickle ventilator (7, 23, 43 and 67 m). The external pressure coefficient is considered equal to 0.6. The total pressure is not sensitive to wind speed variation for wind speeds less than 4 m/s, which is the annual average wind speed for Montreal corresponding to open terrain data. Since the building considered will be located in the downtown area is exposed to even lower wind speeds. Furthermore, natural ventilation will be used from March to November (outside temperature between 10° and 20°C) and thus, the average wind speed for this period is about 2.5 m/s. Therefore, the results are relatively insensitive to the range of wind speeds expected but there are more sensitive to the outside temperature and the height location of the ventilator.

Figure 6 illustrates the total pressure as a function of the external pressure coefficient, outside temperature 10°, 15°, and 20°C respectively and results are given again for four individual heights of the trickle ventilator (7, 23, 43 and 67 m). The wind speed is considered equal to 2.5 m/s. The total pressure is not sensitive to pressure coefficient variations and thus, a pressure coefficient of 0.6 is assumed for the rest of the analysis.

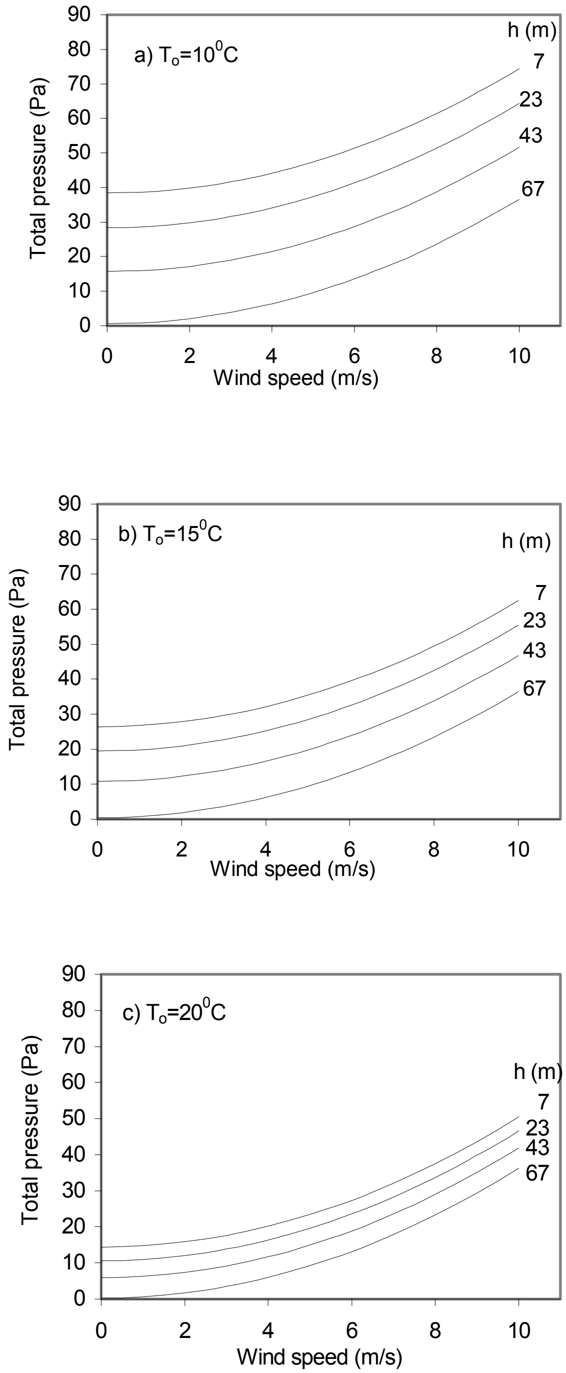

Figure 5. Effect of wind speed on total pressure for different outside temperatures (C_{pe}=0.6).

Figure 7 shows the total pressure as a function of the inside-outside temperature and the results are given for four individual heights of the trickle ventilator (7, 23, 43, 67 m). The pressure coefficient and the wind speed are considered equal to 0.6 and 2.5 m/s respectively.

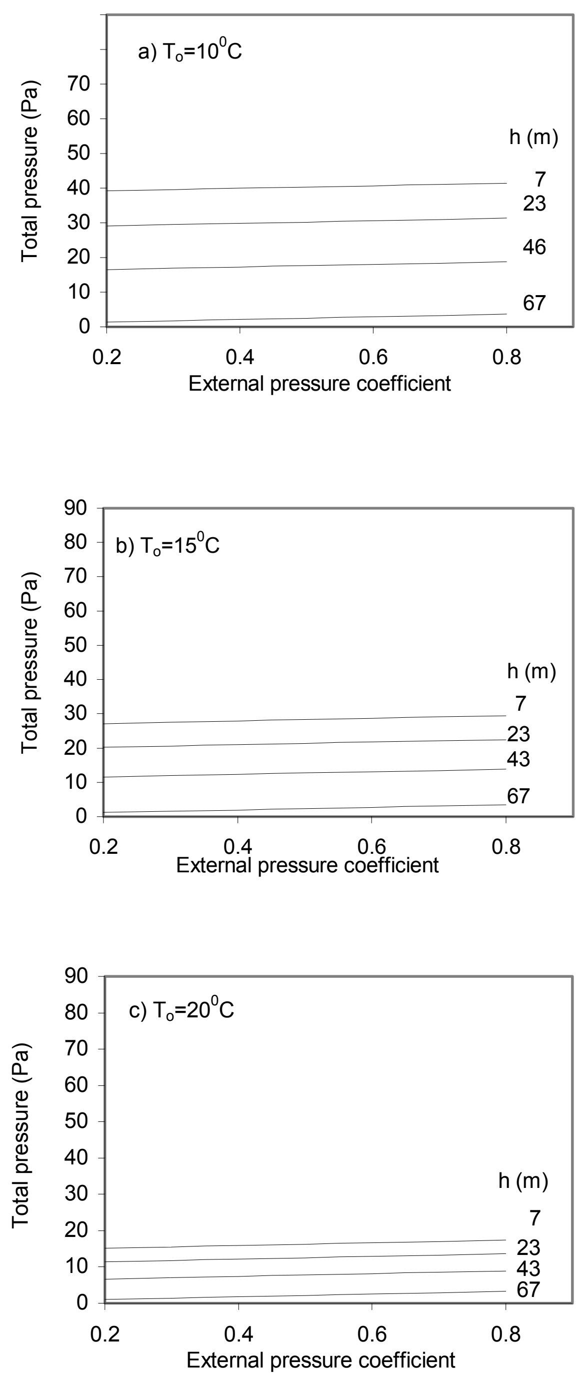

Figure 6. Effect of external pressure coefficient on total pressure for different outside temperatures (V=2.5 m/s).

The total pressure is sensitive to opening height and temperature variations since the simulated building is high-rise and the stack effect dominates in the present case of low wind speeds. However, the stack effect is more dominant at the lower floors as they are farther from the fan.

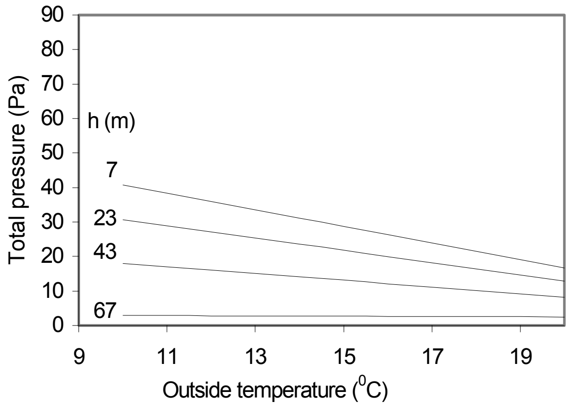

Figure 7. Effect of outside temperature on total pressure.

Simulation results

Based on the methodology described previously, the required opening area was calculated using equation (10). Occupancy equal to one was assumed for the simulations. Only the variation of the opening height and the inside-outside temperature differential was considered since the sensitivity analysis shows that these are the dominant parameters for low wind speeds. Figure 8 illustrates the simulation results for the required opening area at different opening heights and temperature differentials for wind speed and external pressure coefficient equal to 2.5 m/s and 0.6 respectively. It is observed that:

- for high outside temperature (20°C), the required opening area varies from 55 to 85 cm^2 between the 2nd and the 13th floor respectively;
- for small outside temperature (10°C) the required opening area varies from 35 to 62 cm^2 between the 2nd and the 13th floor; and
- for outside temperature of 15°C, the required opening area varies from 40 to 70 cm^2 between the 2nd and the 13th floor respectively.

Hence, the required opening area of the trickle ventilators to supply 10 L/s per person [8] in the office space shown in Figure 2 is most of the time higher than the 48 cm^2 opening area recommended in the BRE Digest 399 [2]. This discrepancy is due to the lower fresh air requirement of 5 L/s per person recommended by BRE [2].

In general, a larger opening area is required at the upper floors to reduce the resistance of the opening and to increase the air flow due to stack effect and thus to reduce the operation of the fan. On the contrary, smaller area is required at the lower floors to prevent possible overflow due to large stack effect and potential over-pressurization. There is no risk for draft if a large opening area is used at the upper floors (e.g. 85 cm^2), because of the design of the slot ventilators with air cavities and due to the exterior mesh (small effective area). Furthermore, large opening areas are required for high outside temperatures, when the outside air is warm and cold drafts are not expected to occur.

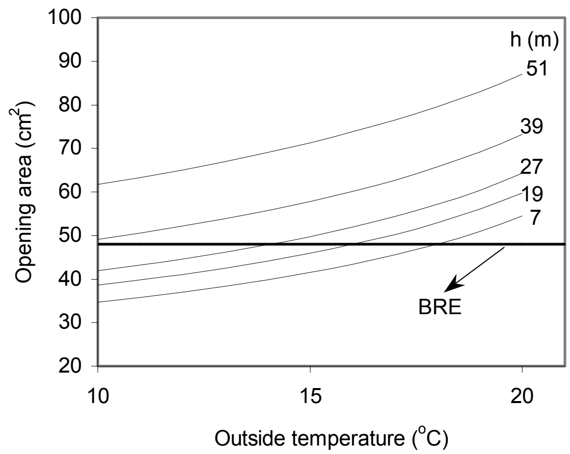

Figure 8. Opening area as a function of the outside temperature.

For an approximate selection of the opening area, assuming that the design outside temperature is 15°C, 60 cm^2 is recommended; this corresponds to 5 cm^2 per m^2 of floor area. With this size selection there is a risk for overflow at the lower floors for outside temperature around 10°C (large stack pressure) while insufficient air flow may be observed at the upper floors for outside temperature between 15 and 20 °C (small stack pressure). The best option, in order to prevent from these potential discomfort problems, is to control the opening area with a damper installed on the exterior part of the trickle ventilator, although this may be expensive.

Therefore, for the particular case of Montreal and occupancy less than 12 m^2 per person, at least 5 cm^2 opening area per m^2 of floor area is recommended for spaces similar to the simulated space. For large office spaces with unknown occupancy, the use of dampers is desirable to ensure an acceptable comfort level. Furthermore, to avoid possible drafts when large opening area is required, two or more ventilators (instead of one) located on the same wall are recommended.

CONCLUSIONS

This study presented simulation results regarding the potential of trickle ventilator integration in ventilation design of office buildings. The sensitivity analysis showed that the opening height and the outside temperature are the dominant parameters in the ventilation design of high-rise buildings for wind speeds lower than about 4 m/s. On the basis of the results of a case study, the main conclusions regarding the integration of trickle ventilators in hybrid ventilation are the following:

(i) The opening area of trickle ventilators should be selected as a function of fresh air requirements, height, design conditions and control system. For the particular case of Montreal and occupancy less than 12 m^2 per person, at least 5 cm^2 opening area per m^2 of floor area is recommended for relatively small office spaces.

(ii) For proper control of fresh air intake through the trickle ventilators, inlet or exhaust dampers in conjunction with fan speed control may be utilized.

ACKNOWLEDGEMENT

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