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Multizone Airflow and Contaminant Modeling: Performance of Two Common Ventilation Systems in Swedish Apartment Buildings

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ABSTRACT

The goal of this work was to assess the performance of two common ventilation systems, an exhaust and an exhaust-supply system, in Swedish apartment buildings. Since correct air-exchange and interzonal airflows are important for removing contaminants and improving indoor air quality, these airflows were analyzed by systematic computer calculations when selected input parameters were varied around their default values. The research specifically involved establishing characteristics of a prototypical building, determining appropriate boundary conditions (climate and operation), developing necessary physical/mathematical models, and establishing a protocol for carrying out the parametric studies required to assess airflows in buildings of this type.

The prototypical building represents a typical six-story apartment building. It is equipped with a low-velocity ventilation system, either an exhaust or an exhaust-supply system. Because of the lack of reliable key data, it was a difficult and time-consuming process to establish the building. Although there is a need for better quality leakage data of multizone structures and their individual components, parametric studies are somewhat forgiving in this regard.

A steady-state multizone airflow model was designed to simultaneously solve the airflows through the building envelope, between different zones, and in the duct system. In addition, a contaminant model was developed and coupled with the airflow model. It calculates contaminant concentrations over time in every defined building zone. Model validations show that both models can be expected to produce reliable results.

The study results, though specific for the prototypical building, present useful generalities that allow substitutions to be made in working with comparable buildings. The exhaust ventilation system allows a pressure hierarchy that is beneficial for controlling interzonal airflows and exfiltration. This hierarchy, however, turns into a disadvantage when leakage levels are altered by closing ventilation slots, for example. The exhaust-supply ventilation system has the advantage of guaranteeing a minimum air-exchange rate under all conditions. A drawback of this system is that air flows from apartments on the lower levels to apartments on upper levels via the staircase. Because of this flow pattern, contaminants can be transported to upper-level apartments.

INTRODUCTION

One of the main purposes of ventilation in buildings is to supply and extract air in such a way that contaminants are removed and indoor air quality is improved. Before the early 1980s, however, our ability to simulate the performance of ventilation systems was somewhat limited because computer programs for interzonal airflows in buildings were not readily available. A 1983 review (Herrlin 1983) found no detailed program in the public domain. This finding eventually led to the development of the multizone airflow program described in this paper. Between 1983 and 1992, a considerable number of airflow programs, many of good quality, were designed around the world (Feustel and Dieris 1992). Since then, several of these programs have been developed into powerful tools for airflow and contaminant modeling (Feustel 1996; Walton 1997). Although the present paper is based on research completed in 1992 (Herrlin 1992), the number of extensive parametric studies conducted using these simulation tools is still small.

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A considerable amount of good quality data is available for duct components; however, the data show a large spread regarding the pressure loss coefficients. Equations for the coefficients were fitted to data based on measurements of simplified components. First, the accuracy of the fitted equations was estimated in reference to the measured data. Second, the fitted equations were compared to commercially available components. This two-step procedure gave an estimate of the quality of the fitted equations; they are estimated to have typical errors of less than ±25% compared to commercial components.

The pressure drop and pressure distribution in the duct system as well as the fan's performance curve can have significant influence on the stability of the airflow in the ventilation system. High pressure drops in registers and distributors stabilize the duct flows against general disturbances, whereas high pressure drops in the vertical trunk can increase this problem. The design pressure drops for the most remote airflow devices were assumed to be 50 Pa (0.20 in. of water) for air distributors and 100 Pa (0.40 in. of water) for exhaust registers.

BOUNDARY CONDITIONS

The boundary conditions can be classified into three major groups: weather data, pressure coefficients, and indoor climate. The weather data used in this study are based on 20 years of measurements by the Swedish Meteorological and Hydrological Institute. For Stockholm, the yearly average temperature and wind velocity are 6°C (43°F) and 2.8 m/s (6.3 mph), respectively. Temperatures below the annual 1 percentile frequency of occurrence (–15°C [5°F]) and wind velocities above the annual 99 percentile (7.2 m/s [16.1 mph]) are not considered. Wind perpendicular to the front facade was selected as the most useful single wind direction based on airflow variations in the building.

Wind creates a pressure field on the outer surface of a building. The pressure distribution depends on many factors, such as wind velocity, wind direction, geometry of building, overall roughness of terrain, and immediate surroundings. A building of the type and size of the prototypical building is most likely to be built in an urban environment. An appropriate wind profile for such an environment was selected. The shielding afforded by nearby obstacles modifies the impact of undisturbed wind and, consequently, results in different pressure coefficients.

Dimensionless pressure coefficients relate the wind-induced change in static pressure at a given point on the building shell to the dynamic pressure of the undisturbed wind at the roof level of the building. All surface pressures are considered to be temporal mean values. The coefficients used in this work were calculated with a computer program that is based on numerous measurements in wind tunnels (Grosso 1992). Since using an average value for a whole facade may introduce errors, the pressure pattern over the facades of the end section was simulated by employing 36 pressure points covering areas of equal size.

In modern residential buildings, temperatures between 20°C (68°F) and 26°C (79°F) are likely to satisfy most people's comfort needs (ASHRAE 1992). Since Swedish apartment buildings are not air conditioned, the indoor temperature will vary with outdoor conditions. For this study, however, an indoor temperature of 20°C (68°F) was chosen.

AIRFLOW PROGRAM

The steady-state airflow program that was developed for this study simultaneously determines the flow balance in a multizone building and its ventilation system. This program predicts the airflow through leaks and openings in the envelope, floors, and partitions as well as the airflows in the duct system. Driving forces accounted for are wind load, thermal buoyancy, and fan pressure. The program also includes a simple dynamic contaminant model.

Airflow Model

The airflow model is based on a network model where pressure nodes are interconnected by flow links. The program calculates a flow balance in each inner node. These nodes are points having unknown pressures, such as zones and certain duct components. Any group of rooms, such as in an apartment, can be described as one zone if the flow resistances between the rooms are considered small in comparison to those of the apartment envelope. Links are leaks, openings, and ducts. For a link between an inner node and the outside, an outer node is defined. Unlike inner nodes, outer nodes have known pressures as determined by the pressure distribution around the building.

The standard power-law formulation for describing airflow rate as a function of pressure difference is applied to all flow links. For building leaks, Tamura and Wilson (1967) have suggested a correction factor that takes into consideration current temperature and atmospheric pressure. Herrlin (1986) measured the pressure drop across filters and coils of an air-handling unit in a laboratory environment. The measurements indicated that a satisfactory flow rate can be estimated from the pressure drop across the component by using the same density- and viscosity-corrected power-law formulation. Because of the lack of input data for specific buildings, however, this multizone model is better suited to parametric studies where the changes of input parameters are of more interest than their absolute values.

Once the structure and ductwork have been broken down to pressure nodes interconnected by flow links of the power-law type, one common, well-defined system of equations can be assembled to determine all unknown inner pressures. For the numerical solution of the airflow balance to be produced efficiently, it is important that the building structure and duct system be modeled in similar ways and that the computer code be rationally organized and programmed (Bring 1992).

As a steady-state model, all driving forces are considered to be constant during each time step; thus, algebraic equations can be used rather than differential equations. The model predicts the airflow rates in a building by solving a nonlinear system of equations. Usually, the standard Newton-Raphson method works satisfactorily, although the convergence is sometimes slow. The mathematical solver in the airflow model uses this method but, in exceptional cases, modifies it to ensure fast convergence. This modified method uses a search routine where the direction of search is determined by the Newton-Raphson step and the distance of movement is determined by minimization of a related scalar function (Lindberg 1985). An efficient skyline-Gaussian method is incorporated in the solver to handle the resulting system of linear equations. The result was a fast and reliable solver that stood up well against other methods (Herrlin and Allard 1992).

Model Validation

The aim of any model validation is to establish the accuracy of the model predictions by comparing the values produced against actual measurements. A major obstacle in validating a steady-state model is that dynamic effects cannot be modeled. This limitation has to do with our lack of understanding of the complex dynamics of airflows through multizone buildings and does not mean that dynamic effects are not important. Dynamic effects are typically caused by changes in wind velocity and/or direction, pulsations in fans, and doors that are opened and closed.

Dynamic effects without the influence of compressibility can be treated as a quasi-steady-state process by choosing a time interval between airflow calculations that is small compared to the time variations associated with dynamic processes. An integrated pressure difference, however, will introduce an error in the flow because of the generally nonlinear flow functions. The error caused by applying integrated pressures on the nonlinear system was estimated to be about 8% before flow reversal occurred. Even under linear conditions, the averaging procedure causes errors if flow reversal occurs. Flow reversal appears to dominate the dynamic effects, and its impact on air-exchange rates is not negligible. Under highly turbulent conditions, therefore, steady-state assumptions can introduce significant errors. Accordingly, certain simulations need to be performed with caution.

Although an absolute validation cannot be performed, validation methods are useful in eliminating large errors, checking that the trends indicated are reasonable, and establishing the potential range of applications. In many fields, models are routinely accepted as approximations of reality that, although they cannot receive absolute scientific validation, are still extremely useful (Judkoff 1988). The user of any model has to recognize that its predictions will have a degree of uncertainty. The validation methodology selected for the airflow model is based on three well-established techniques: analytical verification, empirical validation, and intermodel comparison. An intermodel comparison performed with another airflow model (Walton 1989) produced identical results for all test cases (ranging from 2-zone to 45-zone structures). The overall validation result suggests that the model can be expected to produce reliable results, especially for a well-sealed, mechanically ventilated structure such as the prototypical building used here.

Contaminant Model

The dynamic contaminant model calculates the contaminant concentration over time, in every defined zone of a building. In the steady-state airflow program, contaminant concentrations can be studied over time as long as the airflows are constant for each calculation.

The calculation of contaminant concentrations is based on initial concentration in each zone, contaminant source or sink in each zone, contaminant reduction in flow between zones, and constant concentration outdoors. Furthermore, the contaminant model assumes that instantaneous perfect mixing occurs within each zone—in other words, the contaminant concentration in the air leaving a zone is equal to the average concentration in that zone. Therefore, this model cannot be used for ventilation efficiency studies.

The model predicts the contaminant concentrations in a building by using a set of coupled, first-order, ordinary differential equations. It is an initial value problem; we know the zone concentrations at starting time. All parameters are assumed to be constant during the dynamic calculation for each set of airflow rates given by the steady-state airflow model. An intermodel comparison performed with a similar model (AIVC 1990) produced identical results.

PARAMETRIC STUDY

Today's state-of-the-art airflow models are well suited for parametric studies. Although gathering measurements on an actual building could theoretically give similar results, this procedure is associated with many practical difficulties. Furthermore, it does not allow input parameters to be varied so that their influence on a variety of outputs can be ascertained.

Calculations made with airflow models often involve many parameters, some changing simultaneously. The complex interaction among different parameters may be virtually impossible to predict without actual calculations. Surprising results that are difficult to explain can occur, in which case a careful analysis must be performed. Furthermore, a general problem with most simulation models is that a large amount of output is available and it is not always obvious which data to select. The present study was primarily directed to questions about air-exchange and airflow rates under different inner and outer disturbances.

Outside air is defined as air entering the zone directly from outside without passing through other zones. The choice of air-exchange rate based on outside air is rational and is in accordance with the Swedish Building Code for ascertaining air-exchange rates in buildings; an implicit valuation of the air quality of different flows is built into this approach, however. Note also a positive flow being defined as a flow to the apartment and a positive pressure difference being defined as giving a positive flow.

source apartment. Overall, the E system acts as a good guard against contaminant spread from one apartment to another.

The ES-ventilated building exhibits a different flow behavior because of its less-developed pressure hierarchy. Air enters the staircase from the apartments on the three lower floors and exits the staircase to the apartments on the upper three floors (compare Figure 4 for 6°C [43°F] and 0 m/s). The outflow from apartment 01 is nine times larger than that in the E-ventilated building and causes apartment 11 to have a concentration more than three times higher after 12 hours. Consequently, the contaminant concentration in the source apartment is lower than in the E-ventilated building. Apartment 03 will also have a lower concentration because of the lower concentration leaking from apartment 01. The ES system is less able to contain the contaminant source, and elevated contaminant levels occur in apartments many floors from the source apartment.

Figure 6 shows the contaminant concentration transients for apartments 01 (source), 03, and 11 during the first 12 hours after a local two-hour pulse source was introduced in apartment 01. As can be seen, the concentrations for the two first hours are identical to those depicted in Figure 5. The concentration peaks in apartment 03 and 11 were delayed about 0.5 and 2.5 hours, respectively. The E-ventilated building reacted more slowly, i.e., it took slightly longer for the contaminant to be transported through this building. Even if the source is removed and no remedial measures are taken, contaminant concentrations in other apartments can peak hours later; if the source is toxic, this may have serious consequences.

Normal Operation

Airflows in a building can be affected simply by normal operation of the building and its ventilation system. Such factors are not compensated for when a ventilation system is balanced. For purposes of this study, most changes were introduced at the reference climate (6°C [43°F] and 0 m/s wind) to isolate their influence on the airflows from those of climatic changes. Normal changes were introduced in the prototypical building and its ventilation system, and subsequent changes in airflows were determined for apartments 01, 02, 11, and 12.

Enhanced Range-Hood Exhaust. Enhanced range-hood exhaust creates pressure differences that limit the spread of odors and humidity from cooking; however, problems may arise if the pressure differences get too large. Enhanced exhaust has been reported to create very large pressure differences across floors and partitions, as high as 100 Pa (0.40 in. of water) in some cases. For the prototypical building, the pressure differences at enhanced exhaust were compared to those at normal exhaust for the two ventilation systems.

Figure 7 shows the pressure differences occurring across the facade, the partition to the staircase, the partition to apartment 02, and the floor to apartment 03 when the exhaust is enhanced in apartment 01. The exhaust in this case is assumed to increase the total exhaust flow rate from the apartment by 70%. As can be seen, neither ventilation system produces extreme pressure differences across the envelope of apartment 01; the highest pressure difference was found to be below 20 Pa (0.08 in. of water) for the E-ventilated apartment and below 10 Pa (0.04 in. of water) for the ES-ventilated apartment. Both systems, however, ensure a well-protected and well-isolated unit. For the ES-ventilated apartment, the airflow to the staircase is reversed when the exhaust is enhanced.

For the E-ventilated building, enhanced exhaust in apartment 11 causes the same magnitude of pressure difference as shown in Figure 7, except in the case of the partition to the staircase where the stack effect increases the pressure difference to 17 Pa (0.07 in. of water). The maximum pressure difference across the envelopes of apartments 01 and 11, however, occurs across the facade in apartment 01.

The E-ventilated apartment might have draft problems from the ventilation slots because of the pressure drop across the facade of almost 20 Pa (0.08 in. of water) that increases the flow rate through the slots by 37%. This situation may contribute to people's tendency to close these slots. Therefore, Figure

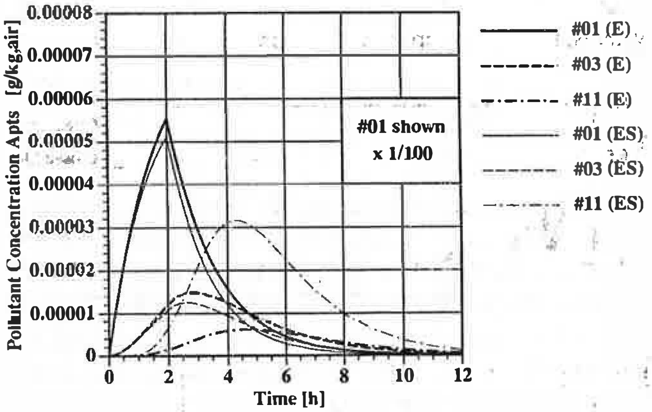

Figure 6 *Contaminant concentration transients caused by a local two-hour pulse source introduced in apartment 01 at time zero.*

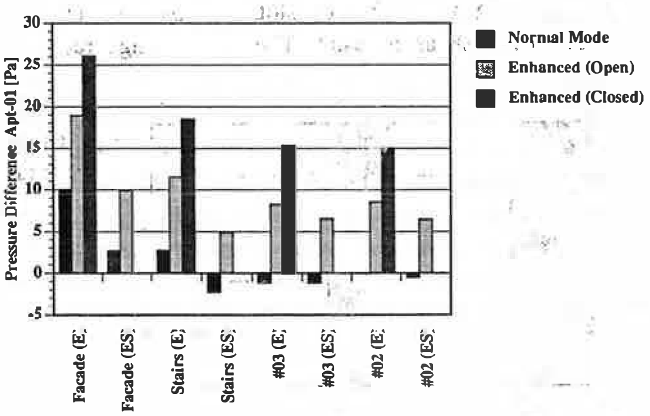

Figure 7 *Pressure differences across envelope of apartment 01 for normal and enhanced range-hood exhaust.*

7 also shows the pressure differences occurring across the envelope of apartment 01 when the ventilation slots are closed. In this case, also, the pressure differences did not reach extreme levels.

A common method of controlling the influence of disturbances on duct flow rates is to increase the pressure difference across the exhaust and supply air devices; the flows are stabilized by a higher pressure drop. There are side effects, however. A higher overall pressure in the duct system will result in the need for a larger fan. Furthermore, the duct leakage will increase.

Among the changes associated with normal operation of the building, the enhanced range-hood exhaust has the largest influence on the exhaust flows in adjacent apartments. This disturbance provides a good measure of the benefit of having a large air device pressure drop. Therefore, the effect of r ducing the design pressure drop across the exhaust and supply air devices by 75% was analyzed.

Figure 8 shows the effect of the air device pressure drops on the exhaust and supply flow rates in apartment 02 when the exhaust is enhanced in apartment 01. For the register flow rate, the stability is about the same for the E and ES systems; the reduction of flow rate is about 7% for the default pressure device and almost 12% for the low-pressure device. The reduction of the flow in the low-pressure distributor is almost 4%. These findings suggest that a pressure drop across the register and distributor of 25 Pa (0.10 in. of water) and 12 Pa (0.05 in. of water), respectively, is too low if the goal is to limit flow disturbances to 10%.

Closed Ventilation Slots. It is not uncommon for people to close ventilation slots; one reason is to avoid drafts during the winter season. As already noted, enhanced range-hood exhaust in apartment 01 increases the airflow rate through the slots by 37%. The consequences of closing the ventilation slots (in one apartment at a time) on the air-exchange rate will be assessed in the top and bottom units.

The air-exchange rate for apartment 01 is reduced by 15% to a value of 0.48 ACH when the slots are closed; the exhaust rate decreases 2% as a result. The air-exchange rate and exhaust flow rate in other apartments were influenced marginally in most cases. The air-exchange rate in the adjacent apartment 02 increased by 4% because of air leaks to apartment 01. Accordingly, closing the slots in apartment 01 cannot, by itself, be harmful for this apartment or any other apartments in the building.

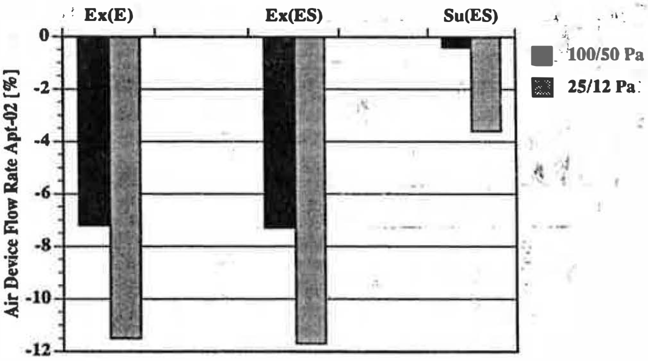

Figure 8 Effect of air device pressure drop on device flow rate in apartment 02 when exhaust is enhanced in apartment 01.

The same calculations were repeated in apartments 02, 11, and 12 with ventilation slots closed. The results, shown in Figure 9, show that the corresponding reductions in air-exchange rates for apartments 02, 11, and 12 were 25%, 14%, and 23%, respectively. Especially for the inner, top apartment 12, closing ventilation slots resulted in the low air-exchange rate of 0.39 ACH. Because of the stack effect in the staircase, the situation gets even worse when the outside temperature is low. The risk of unacceptable air quality in this unit is apparent.

Fouling in Exhaust Ducts. The supply ducts in ventilation systems are protected by filters in the central air-handling unit and, consequently, the reduction in airflow caused by fouling in these ducts is small. Fouling in the exhaust ducts, however, has been reported to cause considerable reduction in exhaust airflow. For this reason, the question was how large a reduction can we expect in the exhaust flows because of fouling in the exhaust ducts, and how does this imbalance affect the pressure and air distribution in the building.

To answer these questions for the prototypical building, the exhaust duct diameter was simply decreased by 5% and 10% to simulate fouling. These levels should not be interpreted as representing normal levels of fouling; the intention is to look at trends.

No significant difference was observed in airflow rate between the E- and ES-ventilated buildings at the 10% fouling level. The exhaust flow rates from the bottom apartments decreased between 7% and 8%, whereas the exhaust flow rates from the top apartments increased between 2% and 3%. The supply flow rates were virtually unchanged. Figure 10 shows how the exhaust flow rates changed with the level of fouling. Because of the small differences between the two ventilation systems, these data represent an average of both systems.

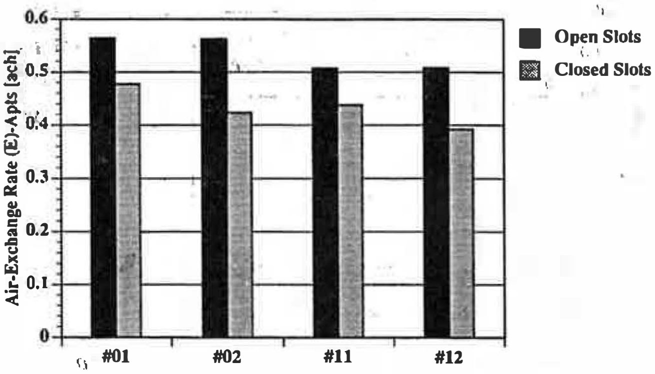

Figure 9 Effect of closed ventilation slots on air-exchange rate for E-ventilated apartments.

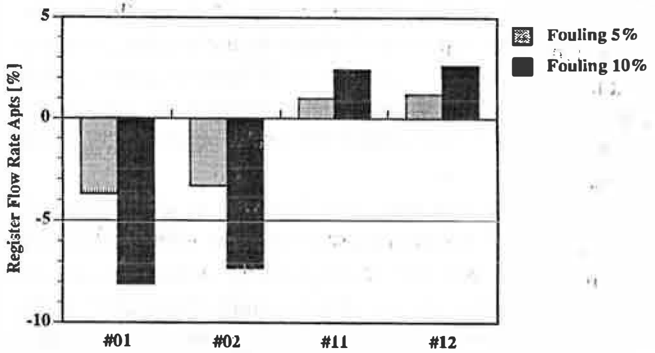

Figure 10 Effect of fouling in exhaust duct on register flow rate for E- and ES-ventilated apartments (average).

There is a potential risk that the reduced exhaust flow and the virtually undisturbed supply flow create overpressures in the ES-ventilated apartments. Figure 11 presents a comparison of the pressure difference across the facade for apartments 01, 02, 11, and 12 at three fouling levels in the exhaust ducts. It is interesting to note that the top apartments, which had low pressure differences across the outer wall when the ducts were clean, were not hurt by the decreased airflow through the exhaust fan. The pressure protection was actually improved when fouling occurred; the exhaust flow rates in these apartments increased.

Fouling of Supply Filter in Air-Handling Unit. Fouling of filters results in higher pressure drops and lower airflow rates. In the prototypical building, the filter on the supply side has a recommended final pressure drop of 150 Pa (0.60 in. of water). The pressure drop across the clean filter is 35 Pa (0.14 in. of water). The final value, therefore, is about four times that of the clean filter. The change in air-exchange rate caused by the increased pressure drop was studied to see whether this final pressure drop is acceptable for the ES system chosen for the building.

From the results, it is evident that the air-exchange rates are almost unchanged throughout the section even though the flow rate through the supply fan and distributors was decreased by 10%. This finding can be attributed to the stability of the exhaust system and the unchanged flow rates in the registers that compensate for the decrease in supply air by an increase in infiltration. In Figure 12, the contribution of supply air and infiltration to the air-exchange rate is compared in apartments 01, 02, 11, and 12 under clean and fouled filter conditions.

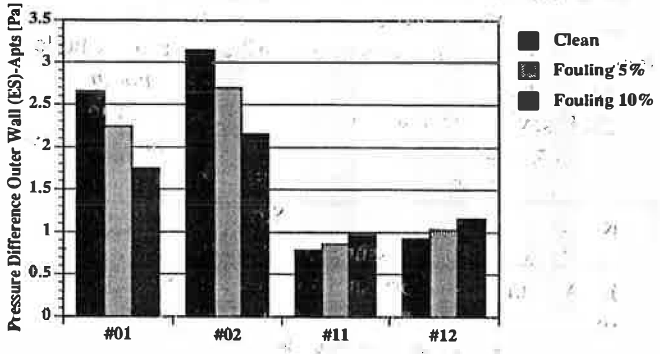

Figure 11 Effect on fouling in exhaust duct on pressure difference across building facade for ES-ventilated apartments.

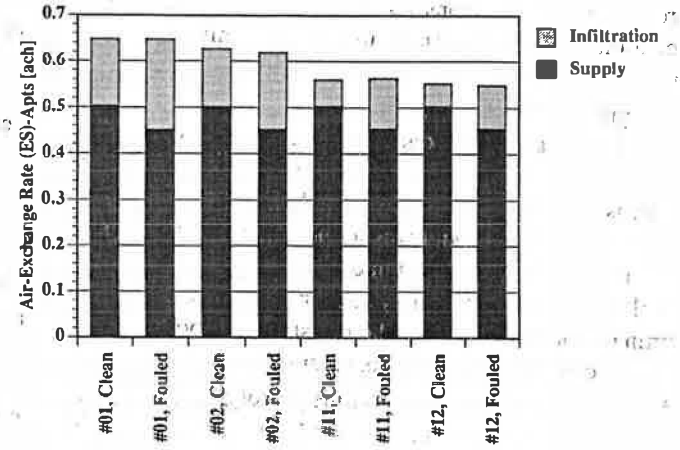

Figure 12 Effect of fouling in supply filter on air-exchange rate for ES-ventilated apartments.

DISCUSSION AND CONCLUSIONS

It was a difficult and time-consuming process to establish the prototypical building. For floor plans, dimensions, and building materials, excellent statistics are available. A considerable amount of good quality data was also found for duct components. As for leakage data, however, very little is available for multizone structures. Although leakage data for windows can be found, leakage data for most other components are sparse and/or of unknown quality. Furthermore, data presently available often give only rudimentary descriptions of these components. The need for better quality measurements on multizone structures and their individual components is critical and certainly requires improved measuring techniques. Because of the lack of reliable leakage data, airflow programs are not being used to their full potential.

The airflow model that was developed is capable of simultaneously assessing the airflows in a multizone building and its ventilation system under steady-state conditions. The building structure and the ventilation system are described in similar ways so that one common system of equations can be solved for all unknown inner pressures. By taking the special characteristics of this system into consideration, a fast and reliable solver was developed.

Under highly turbulent wind conditions, steady-state assumptions can introduce significant errors in airflow rates. Flow reversal appears to dominate the dynamic effects, and its impact on air-exchange rates is not negligible. The error caused by applying integrated pressures on the nonlinear system was estimated to be about 8% before flow reversal occurred. Certain simulations, therefore, need to be performed with caution. Research on the impact of dynamic effects is important.

The problem of finding reliable leakage data and the assumption of steady-state conditions make the airflow model better suited for parametric studies such as the one conducted here than as a tool for evaluating full-scale measurements. The dynamic contaminant model was found to be useful for estimating air movements in the building; it gave a measure of how well the two ventilation systems managed to contain a contaminant source. Model validations show that both models can be expected to produce reliable results.

All results, though specific for the prototypical building, present useful generalities that allow substitutions to be made in working with comparable buildings. Under reference conditions (6°C [43°F] and 0 m/s wind), the air-exchange rate for the entire building section was similar for the two systems. The average air-exchange rate for the exhaust-ventilated apartments, however, was lower than for the exhaust/supply-ventilated apartments, mainly because the air from the staircase is not regarded as outside air. Overall, the weather conditions did not change the airflows much due to the tight structure of the building and its well-designed ventilation system.

The *exhaust-ventilation system* allows a pressure hierarchy that is beneficial for controlling interzonal airflows and exfiltration. Air was transported from outside to the apartments via the staircase; on average, 10% of the air extracted from the apartments in this building originates from the staircase. The system effectively isolated a contaminant source in an apartment. This hierarchy, however, turns into a disadvantage when outer or inner leakage levels are altered. For example, closing ventilation slots can substantially reduce air-exchange rates for apartments on the upper levels.

The risk for extreme pressure differences across the facade, floors, and partitions caused by enhanced range hood exhaust was found to be low; closed ventilation slots elevated the pressure differences without reaching extreme values. A high design pressure drop across the apartment envelopes is important to limit exfiltration; it was demonstrated that a high pressure guard protects the building from exfiltration for most weather conditions. Reducing the design pressure drop across the air devices substantially reduced the duct flow stability when the exhaust is enhanced in an adjacent apartment.

The *exhaust-supply ventilation system* has the advantage of guaranteeing a minimum air-exchange rate under all conditions; the stability of the air-exchange rates, therefore, is higher for this system than for the exhaust-ventilated system. A drawback of this system is that air flows from apartments on the lower levels to apartments on the upper levels via the staircase. Because of this flow pattern, contaminants can be transported to upper-level apartments, air-exchange rates in some apartments can be sharply elevated, and air-exchange rates in the entire building can be higher compared to the exhaust-ventilated building.

The risk was low that the virtually constant supply flow would create an overpressure when fouling occurred in the exhaust ducts in the exhaust-supply ventilated building; apartments that had a low pressure difference when the ducts were clean actually showed improved protection against exfiltration. Fouling of the supply filter in the central air-handling unit did not affect the air-exchange rates for the apartments in this building; because of the stability of the exhaust system, the reduced supply flow was compensated by increased infiltration. Also for this system, reducing the design pressure drop across the air devices substantially reduced the duct flow stability.

ACKNOWLEDGMENT

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