PREDICTING THE PRESSURE REGIMES AND INDOOR-OUTDOOR AIR-EXCHANGE IN A MULTI-UNIT RESIDENTIAL BUILDING

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ABSTRACT

This paper is part of a research project aiming to model the impact of air leakage on pressure regimes, resultant air movement and energy use in high-rise residential buildings using an advanced energy and airflow simulation tool: ESP-r. Simplified simulations for small sections of the building for which experimental data are available are carried out first. Results are also presented for the second stage of the research - transient whole building simulation.

INTRODUCTION

High-rise residential buildings represent 10% of all dwelling units in Canada and are major consumers of energy. On a floor area basis, these buildings consume more energy than single family dwellings - even though the high-rise unit has much less exposed exterior surface. One of the most significant contributors to space heating energy use in most high rise residential buildings is the energy required to heat air leaking unintentionally into the building.

To address the issues of balancing energy efficiency and Indoor Air Quality (IAQ), multi-story residential buildings often have mechanical ventilation systems to provide adequate outside air. The performance of these systems, however, is often less than satisfactory, due to poor design, sporadic maintenance, and interactions with both natural infiltration and occupant behavior (Feustel & Diamond 1998). Modelling studies for high-rise residential buildings are very limited (Feustel & Diamond 1998; Walker 1999; Liu et al. 2005) due to complexities and lack of detailed experimental data to be used as inputs and for validation. In all previous studies the airflow model COMIS (Feustel 1999) was used for the simulation, which did not take into account adequately the buoyancy effects in the high-rise buildings. Methods for controlling stack-driven flows in multi-unit residential buildings are discussed by Lstiburek (2005).

While information on the air leakage characteristics of multi-unit residential buildings is far from complete, data are available that can be used to define the leakage areas in the building envelope. However, there is very little data available on the indoor-outdoor air pressure regimes that drive air movement as a result of stack, wind, and mechanical ventilation forces. In 1999, Canada Mortgage and Housing Corporation (CMHC), in cooperation with the Institute for Research in Construction and the Ottawa Carleton Regional Housing Authority, conducted a testing and monitoring program to determine the leakage characteristics of building envelope openings (fan depressurization and tracer gas tests) and monitor the indoor-outdoor pressure distribution in a high-rise apartment building in Ottawa. Figure 1 is a photo of the actual building. A plan of a typical floor is illustrated in Figure 2.The building's distribution of envelope pressure differences were monitored for almost 15 months along with the on-site weather conditions.

Experimental data (Reardon et al. 2003) indicate that ventilation to the individual units varies considerably even with the mechanical ventilation system operating, since infiltration in high-rise buildings is a complex function of stack, wind and mechanical system effects. Retrofits for the improvement of the operation efficiency of high-rise apartment buildings are difficult due to the lack of information on building envelope pressures and internal airflow patterns.

This paper is part of a research project aiming to model the impact of air leakage on pressure regimes, resultant air movement and energy use in high-rise residential buildings using an advanced energy and airflow simulation tool ESP-r (ESRU, 2002). The

Figure 1. The building - West facade view.

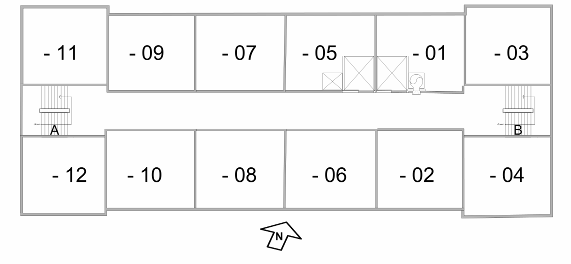

Figure 2. Typical floor plan

ultimate goal of this study is to develop a set of guidelines for the design of a tool that can be used by engineers or retrofit practitioners for the prediction of the airflow patterns and the related energy consumption in multi-family high-rise residential buildings. Simplified simulations for small sections of the building for which experimental data are available are carried out first. Results are also presented for the second stage of the research - transient whole building simulation.

DESCRIPTION OF THE BUILDING

There are 250 residential apartment suites on 21 floors of the 22-storey building. The floor numbering scheme omits a 13th floor, thus the topmost storey is the 23rd floor. A typical floor contains 12 residential suites. The two apartments on each floor that wrap around the elevator shaft are bachelor-style suites with no bedroom. All other apartments are one-bedroom style. The corner suites have their windows and balconies on the east and west ends of the building. All the other middle suites have their exterior façade facing North or South. The building is 41 m long, 16.2 m wide and 59.8 m high. The structure of the building is a combination of steel and concrete construction. Full height concrete L-shaped shear walls enclose each of the four corner suites and the two stairwells, one at each end of the building. There are two side-by-side elevators that operate over the full height of the building and their combined structural shaft is a three-sided concrete shear wall. This central structural shaft also contains the corridor ventilation supply duct adjacent to the west elevator. Ventilation of the building is comprised of a central supply system providing tempered 100% outdoor air to each corridor (one diffuser per storey) and exhaust fans in the kitchen and bathroom of each unit. Supply air then enters the apartments by the undercut of the entrance door of each unit. Several of the common areas on the ground floor also have separate exhaust fans. The air handling unit (AHU) for the corridor air supply ventilation system is located in the mechanical room (suite 205) on the 2nd floor of the building. The corridor supply system's vertical duct is of concrete block construction and runs from the 2nd to the 23rd floor. A gas-fired boiler provides the heat for tempering the corridor air supply through a coil just downstream of the fan in the corridor supply system's air handling unit. The building is heated with electric baseboard heating in each suite and in common areas on the ground floor (Reardon et al. 2003).

METHODOLOGY

A coupled simulation (thermal and airflow) for the whole building using ESP-r requires a large number of zones (more than 100) and changes in the source code. Considering the complexity of the simulation, the large number of zones and input parameters required as well as the uncertainties involved (leakage characteristics of apartment door undercuts and supply registers, airflow through the stairwells, elevators, operation of exhaust fans, occupants' behavior, window openings) it was decided to initially focus on smaller sections of the building for which experimental data are available for validation purposes. At this stage, the stack building envelope pressure is fixed to a specific value for each floor using measured data. The objective is to develop and validate a simplified model in order to extract important information for the airflow patterns inside the building or necessary inputs such as leakage characteristics of openings. Also to identify the most important parameters that should be considered when simulating the air leakage in a high-rise residential building. The results for the simplified model should be presented on a relative basis.

In the second stage, the whole building is modeled. The ventilation shaft, stairwells, and the supply fan are simulated together with the 21 residential floors. The source code (thermal and airflow domain) was modified, i.e. the maximum number of zones and surfaces in the thermal domain was increased as well as the maximum number of nodes and connections in the airflow domain. Leakage characteristics of openings in the building calculated through simulation in the first step are considered as inputs in step 2. The envelope pressures (stack and mechanical forces) are predicted at different elevations and are compared with experimental data. Results for the corridor supply flow rate, building envelope leakage and related energy consumption are presented. Preliminary guidelines for the design of a simplified tool to predict the indoor-outdoor air exchange in multi-unit high-rise residential buildings are also presented.

The stack and mechanical pressures are assumed to be the only driving forces (wind-driven leakage was not considered), i.e. the simulation is performed for one winter day with low wind speeds. This was done in order to keep the number of zones as low as possible (consideration of wind-driven flows requires extra zones for the corner suites) and to eliminate uncertainties attributed to wind pressure coefficients.

<u>SIMPLIFIED SIMULATION</u>

Model description

Each apartment was modeled as one zone assuming closed windows and internal doors open. Walker (1999) found that open interior doors may result in 6% reduction of envelope flows, for the particular multi-family building tested. Most of the leakage occurs around windows (one crack on each suite near the window area, with leakage area equivalent to that measured for the exterior wall); and no leakage between adjacent suites. Walker (1999) reported that the leakage between adjacent suites is less than 5%; Cooke et al. (2005) reported such leakage is insignificant. There are 3 suite types on each floor (1, 2 and 3) with leakage characteristics identical to those of the 3 selected suites tested during the experiments.

Thirteen zones, i.e. one zone for each suite and one zone for the corridor, were considered in the thermal network. Materials for the walls and windows as well as different layer dimensions were extracted from the building drawings. In the airflow network, airflow paths between internal zones and between zones and the outside are specified in the input file along with other information related to ventilation system parameters and building envelope pressures. Six additional fictitious nodes (and zones) are considered in the airflow network, i.e. two fictitious zones for each of the two stairwells and the ventilation shaft. Leakage through the elevator shafts was not considered in the airflow network. However, an equivalent leakage area through the stairwell door undercut was assumed to account for the leakage through the elevators or other unintentional openings in the corridor. There are also four outside nodes (north, south, east and west). A plan of a typical floor and the nodes of the airflow network are illustrated in Figure 3. Each fluid flow component relates the fluid mass flow rate, Q, through the component to the pressure drop, ΔP, across it ($\Delta P = P_{out} - P_{in}$). The power law equation was used to express the flow characteristics of cracks:

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

For the calculation of the airflow through other openings (i.e. door undercuts, supply registers) the following equation was used:

$$Q = C_D \cdot A \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \qquad (2)$$

where C = flow coefficient; n = flow exponent; C_D = discharge coefficient; A = opening area; ρ = air density. Conservation of mass at each internal node is equivalent to the mathematical statement that the sum of the mass flows at such a node is equal to zero:

$$\sum_{k=1}^{k_{i,i}} m_k = 0 \qquad (3)$$

where m_k is the mass flow rate along k^{th} connection

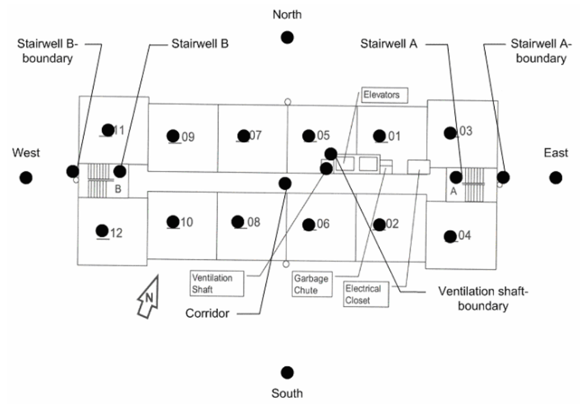

Figure 3. The airflow network nodes.

to node i and $k_{i,i}$ is the total number of connections linked to node i. A detailed description of the ESP-r airflow network is provided by Hensen (1991). Air is supplied from the ventilation shaft to the corridor on each floor through the corridor registers. In the lower floors, the supply air enters the apartments or the stairwells depending on the pressure drops; there is also leakage flow from outside to the different suites. In the upper floors, in addition to the supply air from the ventilation shaft, there is air delivered to the corridors from the stairwells; air enters the apartments via the door undercuts and then it is exhausted to the outside through cracks in the building envelope or through the exhaust fans when operating.

Two sets of experiments were carried out by applying the tracer gas and fan depressurization technique (Reardon et al. 2003) to estimate the building envelope leakage of three selected suites (suite 408 = type 1, suite 2303 = type 2, suite 1409 = type 3). It should be noted that these two methods do not measure the same physical quantity, and assumptions are required to relate the results of one type of test to the other. Analysis of the results shows that the fan depressurization leakage data are overestimated compared to the data from the tracer gas (measured on February 12, 2001); this might be due to difficulties in balancing the pressures in the fan depressurization technique. By comparing the two sets of data corrected values for the leakage characteristics of the building envelope openings for 3 suite types were calculated as presented in Table 1. It should be noted that detailed representation of leakage paths in the building envelope might be more important for wind-driven flows.

First the model is utilized to extract necessary inputs such as the discharge coefficient of the door undercut. Only 3 selected suites (and their adjacent corridor), for which experimental data are available, are modeled. The air exchange rate and the pressure drop across the apartment door ($\Delta P_c = P_{in} - P_{corridor}$) are used to calculate the discharge coefficient of the door undercut (C_D = 0.5). The opening area of the door undercut is 0.02 m^2 and effective leakage area

Table 1
The leakage characteristics of the 3 suite types.

Suite \ Leakage Char.	C (L/s·(Pa)^n)	n
Type 1 (apt -05, -06, -07, -08)	7.9168	0.567
Type 2 (apt -03, -04, -11, -12)	3.6416	0.736
Type 3 (apt -01, -02, -09, -10)	4.21	0.56

(C_D·A) = 0.0095 m^2. A review of the existing literature on discharge coefficients of openings can be found in Karava et al. (2004). Then the 4th (typical floor where infiltration occurs) and the 23rd (typical floor where exfiltration occurs) floor are modeled. The simulation was performed for February 12 2001 (date that winter tracer gas and corridor flow measurements were carried out) with a 5 min time step for the 4th floor and the 23rd floor. The following cases were investigated: phase 1 (corridor supply AHU OFF and local exhaust fans OFF), phase 2 (corridor supply AHU ON and local exhaust fans OFF), phase 3 (corridor supply AHU ON and local exhaust fans ON in suites 408 and 2303). The leakage flow rate and the pressure drop across the building envelope and between each suite and its respective corridor were calculated and compared with experimental results for two suites (suite 408 and 2303). Actual weather data measured on site were used as boundary conditions. The heating load is calculated via thermal simulation for a typical winter design day. Then the baseboard capacities required to maintain the set point temperature are estimated. The required maximum capacity to maintain the indoor temperature at 23 C (set-point) is about 2.5 kW in each apartment. This value was selected based on measurement data for the interior air temperature.

The stack building envelope pressure was fixed to a specific value for each floor. Measured values for the envelope pressure with the fans OFF were used. The measured envelope pressure under winter conditions with the supply and exhaust fans OFF is 18.9 Pa, -6.8 Pa and -18.2 Pa across the building envelope of suites 408, 1409, and 2303 respectively. The theoretical value for the stack pressure assuming that the Neutral Pressure Level (NPL) is near the mid-height of the building (confirmed by experimental data for the pressure difference across the envelope at different heights), outdoor temperature equal to -12.4°C and indoor temperature 23°C (monitored values) is equal to 18.9 Pa, -6.8 Pa, and -37 Pa for suites 408, 1409, and 2303 respectively. The measured envelope pressure is very close to the theoretical value (assuming stack-driven flow only) for the 4th and the 14th floor (typical floor near the mid-height of the building). For the 23rd floor the measured value is smaller which is probably due to the impact of the wind since 2303 is a corner suite on the top floor with more pronounced wind impact. For the 4th and the 23rd floor the input stack pressure was 18.9 Pa and -18.2 Pa respectively. A zero wind speed was assumed. However, the monitored average wind speed during the tracer gas test was equal to 3.1 m/s that correspond to a 4.6 Pa pressure difference on the windward and –1.1 Pa on the leeward wall assuming a pressure coefficient equal to 0.8 and -0.3 for the windward and leeward wall respectively (ASHRAE, 2001). For phases 2 and 3 the same input boundary pressure was used but the "actual" envelope pressure was calculated through simulation by accounting for the mechanical forces too.

Results and discussion

Figure 4 shows simulation results for the envelope ($\Delta P_e = P_{out} - P_{in}$) and corridor ($\Delta P_c = P_{in} - P_{corridor}$) pressures for suite 408 and 2303. The "sign" of the pressure drop across the doorway of the apartment and the building envelope determines whether the supplied air is entering or leaving the apartments. Tables 3 and 4 present experimental and simulation results for the two suites (408 and 2303 respectively). The infiltration or exfiltration flow rate (Q_{env} in L/s and ach) is shown in addition to the envelope (ΔP_e) and corridor (ΔP_c) pressure drop on each suite. Generally, good agreement between the experimental and simulation results is observed. During phase 1 (building operating without mechanical ventilation system) the air mass flow distribution on the two floors follows a predictable pattern. Suites on 23rd floor only receive air from the lower floors, which might impose IAQ problems in the building, while suites on the 4th floor only receive cold unconditioned air via leakage from outside. The envelope pressures in Phase 2 (corridor supply AHU ON and local exhaust fans OFF) indicate that the corridor supply fan successfully pressurized the upper floors, which is most clearly indicated by the "sign" and the increase of the pressure drop acting across the entrance door of suite 2303 (ΔP_c). However, due to the strong stack effect, the corridor supply system did not successfully pressurize the lower floors (i.e. 4th floor). The pressure difference across suite 408 and its corridor indicate that the corridor system operation did not reverse the direction of the flow; nevertheless, the corridor pressurization decreases the envelope pressure and the infiltration flow rate. The negative pressure drops across suite's 408 entrance door (ΔP_c) for phases 1 and 2 indicate that there is no supply air from the mechanical system entering the unit. In phase 3 (corridor supply AHU ON and local exhaust fans ON in suites 408 and 2303), the small pressure difference across the apartment door reveals that the local exhaust fans did not result in interior air in the corridor being drawn into suite 408. Most likely, air flows into the apartments through the building envelope leaks and is exhausted through the fans. For

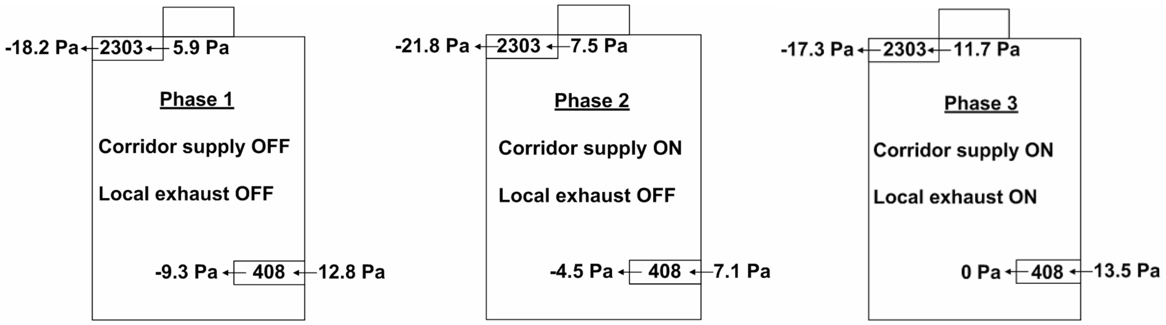

Figure 4. Envelope ($DP_{envelope}$) and corridor ($DP_{corridor}$) pressures for suite 408 and 2303.

these typical winter conditions, the ventilation rates vary between 0.83 and 1.36 ach.

Simulation results indicate that excess air is leaving the corridor through the stairwells (or elevator shafts) on the lower floors, while air is entering the corridor from the shafts on the upper floors. Higher corridor airflows would further increase the leakage from the corridors to the stairwells. This is an expected flow pattern in cold weather due to stack effect, which imposes a significant energy penalty in the building and it should be considered in ventilation system design. The impact of stairwell leakage has also been reported elsewhere (CMHC 1991; Feustel & Diamond 1998). The opening area (effective or equivalent area) and leakage characteristics of the stairwell door undercut and corridor grilles are important parameters since they affect the airflow patterns inside the building. The present simulation has shown that A = 0.1 m^2 and C_D = 0.6 are suitable values for the corridor grilles and the stairwell door undercut. It should be noted that the opening area of the stairwell door undercut is an equivalent opening area including the leakage area of elevator shafts or other unintentional openings in the corridor.

Table 2
Validation for suite 408.

	Q_{env} L/s(ach) sim	Q_{env} L/s(ach) expt	ΔP_e Pa sim	ΔP_e Pa expt	ΔP_c Pa sim	ΔP_c Pa expt
Phase 1	34(1.17)	36(1.24)	12.8	18.9	-9.3	-8.6
Phase 2	24(0.83)	28(0.95)	7.1	9.1	-4.5	-4.8
Phase 3	34(1.17)	41(1.42)	13.5	12.8	0	-1.2

Table 3
Validation for suite 2303.

	Q_{env} L/s(ach) sim	Q_{env} L/s(ach) expt	ΔP_e Pa sim	ΔP_e Pa expt	ΔP_c Pa sim	ΔP_c Pa expt
Phase 1	31(1.05)	27(0.88)	-18.2	-18.2	5.9	8.2
Phase 2	35(1.13)	34(1.12)	-21.8	-21.8	7.5	12.1
Phase 3	42(1.36)	36(1.16)	-17.3	-17.8	11.7	13.1

WHOLE BUILDING SIMULATION

Model description

A simplified 35-zone model of the building (including the ventilation shaft, two stairwells, lobby, corridors and the residential suites) was developed. Each floor was divided into one zone describing the apartments on the South façade, one zone describing the apartments on the North façade, one zone for the corridor, one zone for the ventilation shaft and one zone for each of the two stairwells. In order to keep the number of zones as low as possible, adjacent floors were grouped together, i.e. the South or North façade for floors 3 to 7 is one zone, the corridor for floors 3 to 7 is one zone, the ventilation shaft for floors 3 to 7 is one zone and so on. Floors 8 to 12 are also grouped together as well as 14 to 18 and 19 to 23. This leads to 24 zones. The zoning assumptions are based on results of the first step. The 2nd floor and the lobby are modeled separately (8 and 3 zones respectively). The airflow network consists of 35 internal nodes (described above), 14 external nodes (totally 49 airflow nodes), 14 different airflow components and 57 airflow connections. The ventilation shaft and the two stairwells are divided in different zones assuming fictitious surfaces; these zones are connected in the airflow network through large openings. The opening area of these openings is equal to horizontal cross-sectional area of the shaft or stairwell and the discharge coefficient is equal to 0.65. In the simplified simulation described above, it was found that a suitable value for the (effective) opening area and discharge coefficient of the corridor grilles is 0.1 m^2 and 0.6 respectively (0.5 m^2 for 5 floors grouped together), 0.02 m^2 and 0.5 respectively for the apartment door undercut (0.6 m^2 for 5 floors grouped together) and 0.1 m^2 and 0.6 respectively for the stairwell door undercut (0.5 m^2 for 5 floors grouped together). The leakage characteristics for the 3 suite types presented in Table 1 were used to calculate the total leakage area for each zone.

The simulation was performed for the same day as the simplified one-floor simulation (February 12 2001) with the same time step (5 min). It was assumed that the stack and mechanical pressures are the only driving forces. Actual weather data measured on site were used as boundary conditions. The ventilation air is pre-heated to 21 ºC. This value is based on approximate corridor flow measurements on February 12.

The following two cases are considered:

a) Supply and exhaust fans OFF: there is no supply or exhaust fan operating. Outside air enters the apartments in the lower floors through the building envelope leaks and it is delivered through the ventilation shaft, which acts as a chimney, on the upper floors.

b) Supply fan ON and exhaust fans OFF: The corridor supply AHU is operating. Outside air enters the ventilation system on the 2nd floor and it is delivered from the ventilation shaft to the corridor on each floor; the airflow is distributed to the stairwells or different suites depending on the individual pressure drops available. Experimental data (Reardon et al. 2003) have shown that the supply fan does not operate at the maximum design capacity defined in the mechanical drawings. Both in cold and warm weather the total system flow and the supply flow rates on each floor were typically well below the design specifications (total design flow rate 6800 L/s; design flow rate on each floor = 354 L/s; design flow rate on 2nd floor = 625 L/s). The total measured supply fan flow rate on February 12 is equal to 3800 L/s. In the present study simulations were performed for supply flow rate equal to 2500 L/s, 3150 L/s, 3800 L/s and 6800 L/s.

Results and discussion

Table 4 presents simulation results for the flow rate delivered from the AHU air supply ventilation system through the ventilation shaft to the corridor of each floor on February 12 at 13:00 (time that the corridor flow rates were measured). Experimental data are also presented. Since the floors are grouped in the simulation model, the experimental values for the corridor flow rate were added for every 5 adjacent floors. This may not be the case in reality but it is the only way to compare the simulation with the experimental results. Results are also presented in Figure 5. When the corridor ventilation is shut down (fan OFF), the supply duct (ventilation shaft) behaves like a chimney. Table 4 shows results for the flow rate delivered through the ventilation shaft on each floor – upper floors (or from the corridor to the shaft – lower floors) with the supply fan OFF. Simulation results for the envelope pressures at different elevations are presented in Table 5 and results for the envelope leakage in Table 6.

Table 4 and Figure 5 show that the strong stack effect substantially skews the distribution of the corridor ventilation system supply flow rates delivered on each floor, i.e. greater flow rates on the upper floors and lesser flow rates on the lower floors. These differences are more pronounced with the supply fan OFF or with the supply fan ON and low flow rates, i.e. substantial differences in the supply flow rate between upper and lower floors for Q = 2500 L/s compared to Q = 3150. For Q = 3800 L/s there is almost uniform flow distribution between the different floors. However, the experimental results (Q= 3800 L/s) show differences in the corridor supply flow rate between the floors (Reardon et al. 2003). This difference between the experimental and simulation results can be explained as follows:

(a) The corridor flow measurements were made using handheld instruments and are therefore subject to experimental uncertainties. They should therefore be used only for observing trends in flow behaviour (Reardon et al. 2003).

(b) The corridor in the upper floors is pressurized due to the airflow from the lower floors through the stairwell. Part of this flow may be directed from the stairwell to the outside through building envelope cracks. However, this effect was not modelled since information for the stairwell leakage is not available. Exploratory simulation results confirm that when the stairwell leakage is modeled the corridor flow to the upper floors is increased.

(c) The baseboard capacities are calculated from the loads. Therefore, the thermal behavior of the building may have not been modelled properly. This may have caused an underestimation of the flow on the upper floors.

(d) Several assumptions made on the zoning of the building (i.e. grouping of floors) in order to simplify the model may have introduced errors in the calculation of corridor flows. However, the good agreement between the experimental and simulation results (comparison of Table 5 to Tables 2 and 3) for the envelope pressures indicate that the actual flow rate was probably close to 3200 L/s and not equal to the measured value, i.e. 3800 L/s.

Table 5 shows that the corridor supply system did not successfully pressurize the lower floors due to strong stack effect. Nevertheless, the corridor pressurization decreases the envelope pressure and the infiltration flow rate (compared to the case with the supply fan OFF). The NPL of the building with the supply fan OFF is between 8 to 12 floor (probably close to the 10th floor), as mentioned in the experimental results by Reardon et al. (2003) The NPL with the supply fan ON is between the 6th and 9th floor probably close to 8th floor for Q = 2500 L/s and close to 6th or 7th floor for Q = 3150 L/s and Q = 3800 L/s. Experimental results indicate that the NPL was located close to the 7th floor with the mechanical system operating, thus, there is good agreement between the experimental and simulation results with respect to the envelope pressures. If the supply fan operates at its full design capacity the NPL of the building is close to the 2nd floor.

Figure 6 shows the total infiltration load (kWh) for the building for one cold winter day (February 12) for

Table 4. Corridor supply flow rate for different floors (February 12, 2001).

		Fan ON					Fan OFF
		Q = 2500 (L/s)	Q = 3150 (L/s)	Q = 3800 (L/s)	Q = 6800 (L/s)	Expt.	-
Floor	Node height (m)	$Q_{corridor}$ (L/s)	$Q_{corridor}$ (L/s)	$Q_{corridor}$ (L/s)	$Q_{corridor}$ (L/s)	$Q_{corridor}$ (L/s)	$Q_{corridor}$ (L/s)
2	3.45	72.1	126.3	175.5	370.7	99	-173.5
3 - 7	10.35	293	578.6	840.1	1892.2	375.6	-814.2
8 - 12	21.85	594.5	740.9	893.8	1567.9	674.5	181.4
14 - 18	33.35	657.8	764.2	881.3	1421.8	1171	883.8
19 - 23	44.85	856.6	938.4	1032	1493.4	1500	1335

Table 5. Envelope pressure for different floors (February 12, 2001).

		Fan ON				Fan OFF
		Q = 2500 (L/s)	Q = 3150 (L/s)	Q = 3800 (L/s)	Q = 6800 (L/s)	-
Floor	Node height (m)	ΔP_e (Pa)	ΔP_e (Pa)	ΔP_e (Pa)	ΔP_e (Pa)	ΔP_e (Pa)
2	3.45	13.4	11.36	9.31	1.64	18.16
3 - 7	10.35	7.86	5.94	4.05	-2.25	11.73
8 -12	21.85	-2.06	-3.83	-5.67	-12.56	0
14 - 18	33.35	-13.73	-15.31	-16.98	-23.58	-12.265
19 - 23	44.85	-24.24	-25.73	-27.33	-33.68	-23.46

Table 6. Envelope leakage for different floors (February 12, 2001).

		Fan ON				Fan OFF
		Q = 2500 (L/s)	Q = 3150 (L/s)	Q = 3800 (L/s)	Q = 6800 (L/s)	-
Floor	Node height (m)	Q_{env} (L/s)	Q_{env} (L/s)	Q_{env} (L/s)	Q_{env} (L/s)	Q_{env} (L/s)
2	3.45	-282.4	-289.1	-224.4	-75.6	-340.9
3 - 7	10.35	-1133.6	-1082.4	-750.6	520.6	-1453.6
8 - 12	21.85	494	725.6	925	1516.4	-84.2
14 - 18	33.35	1602.2	1714.4	1828.8	2242.4	1494
19 - 23	44.85	2281.2	2367.2	2457.2	2797.6	2235

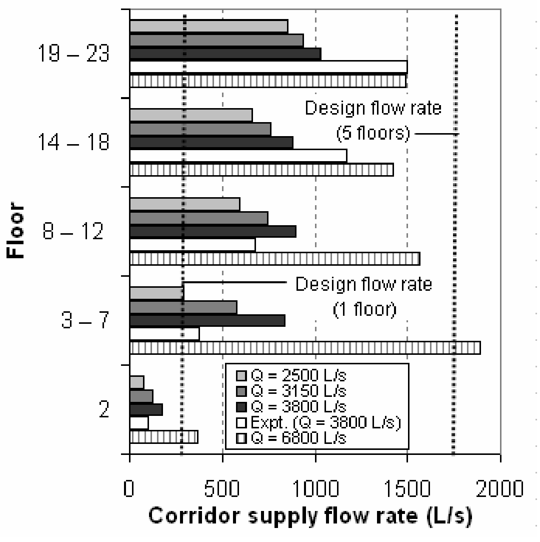

Figure 5. Corridor supply flow rate for different floors (February 12, 2001) with the supply fan ON.

different ventilation scenarios (Fan ON or OFF) and different supply fan flow rates. Note that the infiltration load in the lobby is not considered in this calculation. The total infiltration load is reduced by 24% with the corridor AHU supply operating at Q = 2500 L/s (37% capacity), 35% with Q = 3150 L/s (46% capacity) and 47% with Q = 3800 L/s compared to that with the supply fan OFF. These are data for the tested building and may not be generalized.

A sensitivity analysis was performed to explore the importance of different parameters or the uncertainty attributed to the underlying assumptions. Simulations were performed considering the ventilation shaft as one zone. Results for the envelope pressures are reasonable but predictions for the AHU supply flow rate on the lower floors were not very accurate. The leakage characteristics of the different door undercuts, corridor grilles or intake louver (Fan OFF) affect the airflow patterns inside the building and have a significant impact on the results. It appears that the corridor supply flow rate is an important parameter when simulating the airflow in a high-rise residential building and probably the most difficult to predict, particularly when the fan does not operate at full design capacity.

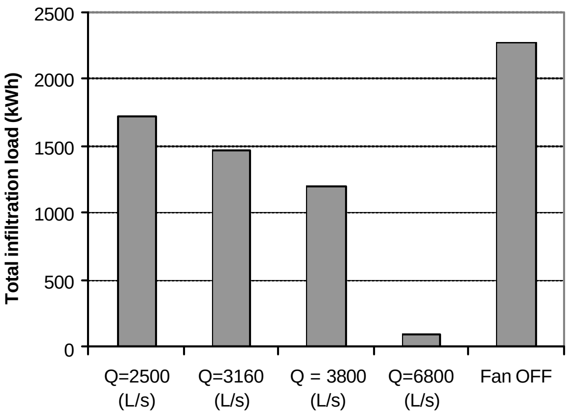

Figure6. Total infiltration load (kWh) for February 12, 2001.

CONCLUSIONS

The reasonably good agreement between the simulation and experimental results particularly considering the complexity of the problem indicates that airflow modelling of such a large building with different airflow patterns is possible in ESP-r. However, it is important that simplified floor simulations are carried out first and that experimental data are available to be used as inputs or for validation.

The stack effect substantially skews the distribution of the corridor ventilation system supply flow rates delivered to each floor, i.e. greater flow rates on the upper floors and lesser flow rates on the lower floors. These differences are more pronounced with the corridor air supply mechanical ventilation system OFF or with the supply fan ON and low supply flow rates. Generally, the flow rate supplied on each corridor is an important parameter when simulating the airflow in a high-rise residential building and probably the most difficult to predict. Note that these are data for the tested building and should not be generalized. Furthermore, calculations are simplified and the assumptions made may have introduced discrepancies in the simulation results.

Further work includes increase of number of zones and comparison of results for different zoning assumptions (i.e. grouping of 2 or 3 floors together). The impact of sub-zoning of the living space and detailed simulation of air flow paths will be investigated. The wind will be also considered and uncertainties attributed to wind pressure coefficients will be explored. Simulations will be carried out for the heating season and results for the envelope pressure will be compared with experimental values.

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