AIR FLOW DISTRIBUTION IN A HIGH-RISE RESIDENTIAL BUILDING

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ABSTRACT

The provision of ventilation air for high-rise multifamily housing has plagued retrofit practitioners and researchers alike. We have been studying the air flows and ventilation systems in high-rise buildings in Massachusetts and in California, and have seen all the horror stories of poorly functioning systems that are neither efficient nor deliver satisfactory ventilation. Frequent problems include the imbalance of supply and exhaust air, the lack of an unobstructed path for supply air, differences in ventilation rates between upper and lower floors and a change in air flow due to seasonal variations in temperature and wind. Based on our diagnostic tests of air flow and air leakage, which we use with our multi-zone airflow computer simulations, we have characterized some common problems and suggest strategies to improve the performance of these systems.

KEYWORDS

Air flow pattern, Air tightness, Modeling, High-rise residential buildings, infiltration, ventilation

INTRODUCTION

To provide good indoor air quality or to calculate space conditioning loads for energy consumption it is important to know the air flow pattern into and within a building. Correct sizing of space conditioning equipment also depends upon accurate air flow information.

The air-mass flows and their distribution in a given building are caused by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems, or a combination of these. But air flow is also influenced by the distribution of openings in the building shell and by the inner pathways. Actions by the occupants can also lead to significant differences in pressure distribution inside a building (see **Figure 1**).

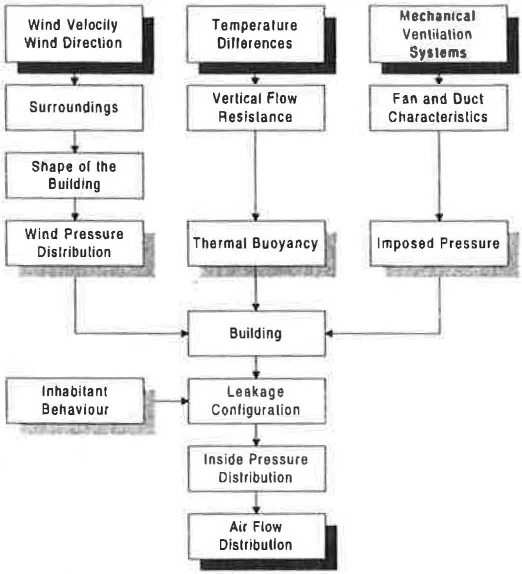

Figure 1 Influences on the Air Flow Distribution in Buildings

Because of the difficulty in relying on infiltration or natural ventilation to provide adequate air for occupants, multi-story residential buildings often have mechanical ventilation systems to provide sufficient outside air for comfort and health. 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. A review of the literature on air flow and air leakage measurements in multifamily buildings in North America is presented in Diamond et al., 1996.

Relying on either mechanical ventilation or infiltration for providing sufficient indoor air quality has an impact on the energy consumption of the building. The effect of infiltration on energy use in a typical high-rise apartment building can be seen directly in Figure 2.

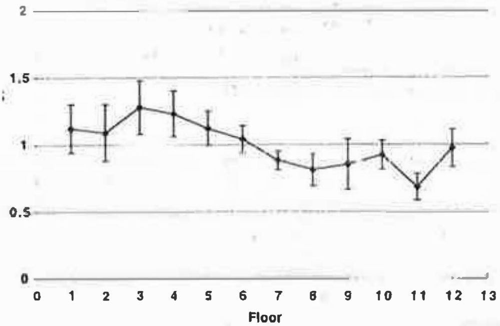

Figure 2 Annual electricity consumption per floor for a 12 story apartment building in Pittsburgh, Pennsylvania. Consumption data have been normalized by mean values. Error bars show one standard deviation above and below the mean.

The figure plots annual energy consumption per floor in a 12-story apartment building in Pittsburgh, Pennsylvania. The energy consumption on the lower floors is 28% higher than the mean, and decreases with height until the next-to-the-highest floor where the consumption is 32% lower than the mean. Energy consumption on the top floor is higher due to conduction losses through the roof. The reason for this variation in energy use is the infiltration of outside air due to stack effect--the pressure differentials caused by inside-outside temperature differences. Apartments on lower floors get a greater burden of outdoor air which imposes an energy penalty in winter. The upper units get warm air from below, but the lack of outdoor air to these units poses an indoor air quality penalty.

In this study we report on the ventilation air flows we have measured and modeled in one high-rise apartment and discuss implications for both energy efficiency as well as occupant health and comfort.

BUILDING DESCRIPTION

The Margolis Apartments is a modern, 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston metropolitan area. The building was designed and built in 1973-1974 and is typical of high-rise construction from that period. The building has thirteen stories and is of steel-frame construction. The individual apartments have electric-resistance heaters in each room, and double-pane windows and sliding balcony doors.

The building has a mechanical ventilation system, with kitchen and bathroom exhaust fans in each apartment vented into separate vertical shafts which have additional exhaust fans located on the roof. The supply air system for the building is provided by a fan and heating unit on the roof that connects to a vertical shaft which has supply registers in the main hallway on each of the floors. Supply air enters the apartments by a slot under the front door of each unit.

The building is exposed on all sides to the wind. Weather data from an airport located within 5 km indicate a mean annual wind speed of 6 m/s with up to 26 m/s wind speeds in winter. The prevailing winds are from the northwest in winter and from the southwest from Spring to Fall.

In December, 1993, the building underwent extensive retrofits. New double-pane windows with low-e glass replaced the old windows throughout the building. A computerized energy management system was installed that allowed for tracking and controlling of the thermostats in the individual apartments. Efficient light bulbs were installed in the individual apartments and in the parking areas. A new sprinkler system was installed throughout the building. Improvements to the abandoned ventilation system were completed a year later.

Prior to the window retrofit, drafts were a major complaint expressed by the tenants. Since the retrofit, there have been--according to building management--fewer complaints about window drafts. The northwest-facing units (weather side) continue to be the hardest units to maintain thermal comfort. Also the second floor units (above the open parking areas) continue to be a problem in cold weather.

MEASUREMENTS & ANALYSIS

The measurements and analysis that we are reporting here consist of four parts: 1) air leakage measurements of the apartments measured pre- and post-retrofit, 2) air flow measurements of the apartments pre-retrofit, 3) pressures and flows between the apartments and the circulation areas and 4) computer simulations of the air flows in the building under different weather conditions.

Air Leakage Measurements

We measured the air leakage in nine apartments, before and after the new windows were installed. The average pre-retrofit total effective leakage area for the one-bedroom apartments was 225 cm^2 and 256 cm^2 for the two-bedroom apartments. The post-retrofit total effective leakage area for the one-bedroom apartments was 230 cm^2 and 248 cm^2 for the two-bedroom apartments.

We note that these measurements, both pre- and post-retrofit, were made in very windy conditions--beyond the limits allowed for standard blower-door tests. While this problem is not uncommon in low-rise buildings, it is an even bigger problem in high-rise buildings, where wind speeds are often much higher than for buildings at ground level.

Air Flow Measurements

Ventilation rates were measured using tracer gas in two apartments in various configurations of exhaust ventilation. With no exhaust ventilation we found typical rates to be about 0.2 air changes per hour (ACH). We also measured the leakage from one apartment to another, using tracer gases, and found little leakage between apartments--less than 4% of the total leakage was to adjacent apartments (Diamond et. al 1996). This result was not altogether surprising given the concrete construction of the building.

These ventilation rates are below the recommended 0.35 ACH given in ASHRAE Standard 62. Operation of the building supply system and the exhaust systems increased the ventilation rate to 0.44 ACH. If the mechanical ventilation systems were operating at their designed flows, the apartment ventilation rates might well meet the ASHRAE standard without excess ventilation.

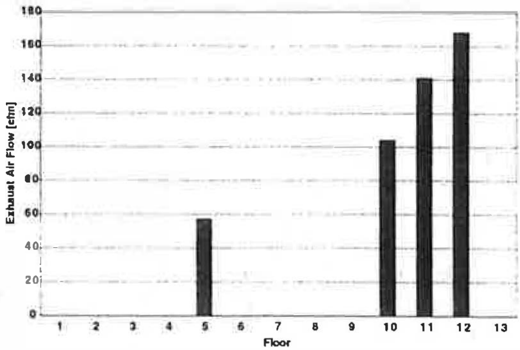

Figure 3. Kitchen exhaust air flow with the local exhaust fans off. Measurements were made at the same exhaust shaft at floors 5, 10, 11 and 12 at Margolis.

Under normal operating conditions, i.e., the local bathroom and kitchen exhaust off, the total exhaust flow in the apartments were between 170 and 442 m^3/h (mean = 247 m^3/h). The mean air flow supplied to the apartments from the corridor was measured at 37 m^3/h, so on average, under these weather onditions, the apartment would be drawing in n additional 204 m^3/h of outside air through ie exterior wall and windows. This over-entilation suggests the need for lowering the oof exhaust fan flow rates.

'emperatures, Pressures and Flows

We measured the temperature of the upply air at the hallway registers for floors 2-3. They were all in the range of 28-30 °C. 'hese temperatures were higher than the etpoint in the energy management control ystem (EMCS) for the air supply, which is urprising, but in fact it serves as a more efficient strategy by providing air heated with he central gas system than the individual electric units in the apartments and, it avoids cold drafts along the corridor floor going into he apartment.

We also measured the post-retrofit supply air flows at the hallway registers and hey were all within a range of 900-1300 m^3/h per floor, with the average matching the design specification for the supply air flow.

The air velocity in the elevator shaft was measured at the top of the shaft at the floor of the penthouse elevator room. The air velocities ranged between 0.7 and 1.5 m/s with both cabs running (regardless of direction) suggesting that the air flow is determined more by wind and stack effect than by the movement of the cabs. The air flow at the top of the elevator shaft during the first measurement was out of the shaft. The direction reversed later in the day, i.e., down the shaft, when the wind shifted direction from the northwest to the northeast.

Inside the building, the air velocity from the elevator shaft into the corridor ranged from 2 m/s at the 13th floor down to 0.7 m/s at he 3rd floor. The temperature in the elevator was 19 °C when the outside temperature was 7 °C. The air velocity at the trash chute at the 13th floor, with the door open, was 4 m/s, upwards, another indicator of the stack effect in the building.

The pressures from the stairwells to the hallway follow the expected pattern of positive pressures to the outside above the neutral pressure level (roughly the midpoint of the building) and negative pressures below, with the profiles of both the north and south towers being similar. The pressure range from -4 to +8 Pascals is relatively small, due to the relatively mild temperatures outside during the measurement (7 °C) and the low wind speeds (Figure 4).

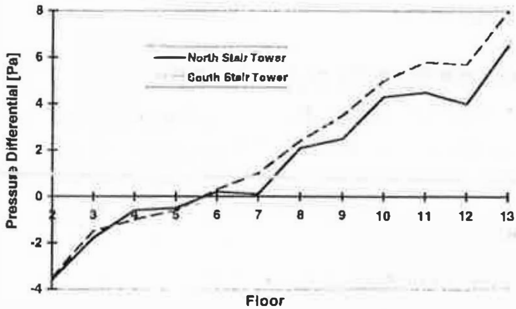

Figure 4. Pressure differences between the stair towers and the hallways at Margolis.

Ventilation Simulations

Based on the measured air leakage data from the building we conducted extensive air flow modeling of the apartments using the multizone air flow model COMIS, a simulation tool, developed by an international group of scientists at Lawrence Berkeley Laboratory, which calculates air flows based on mass balance calculations for individual zones (Feustel and Raynor-Hooson, 1990).

In order to limit the amount of input needed for the simulation model, each apartment was modeled as one zone, assuming the internal doors of an apartment to be open. In order to account for the stack effect and the inter-zonal flows between the floors, all 13 floors were modeled.

The results show, that with wind blowing perpendicular to the windward side and no stack effect present, air moves from the windward side facade through the corridors into the leeward side apartments. Under the previous conditions with no ventilation system present, only a small portion of the infiltration air is exhausted through the vertical shafts of the exhaust system. Dampers at the apartment level and on top of each of the shafts restrict the exhaust flow.

When the building is operating without the mechanical ventilation system, the air mass flow distribution for windward side apartments on different floors follows a predictable pattern. With increasing wind speed, the distribution of infiltration becomes more pronounced, showing a minimum at the third floor and a maximum at the 11th floor.

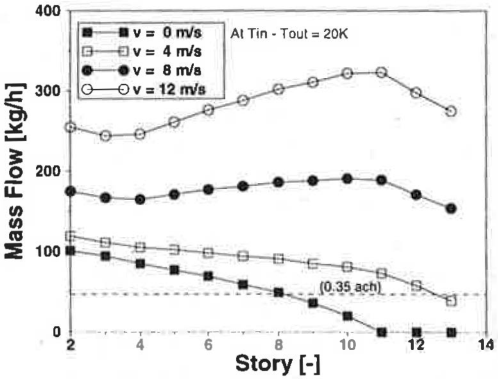

Figure 5. Mass air flow into apartments at different wind speeds and an inside/outside temperature difference of 20 K for the **windward** apartments with the mechanical ventilation system off.

With a larger inside/outside temperature difference of 20 K and zero wind speed, the air flow for the windward apartments decreases with height above ground from 83 m^3/h on the second floor to zero at the level of the 11th floor (Figure 5). With increasing wind speed the air flow curves show a more balanced air flow distribution until the velocity driven air flows override the stack effect. As the pressures forcing the air flow are additive, the air flows for any given wind speed are higher if stack pressure is present.

The air flows for the leeward side are shown in Figure 6. With increasing wind speed the air flow entering the apartments through the outside wall becomes smaller. The zero wind speed curve is the same for the windward side and leeward side. The top floors do not experience any infiltration. Higher wind speeds cause higher negative pressures on the facade, which lower the level for the neutral pressure. At wind speeds of 12 m/s no infiltration occurs at the apartments facing the leeward side.

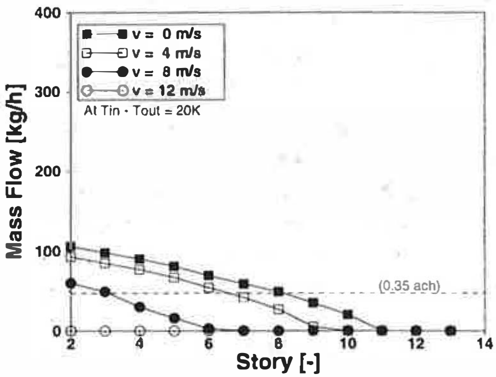

Figure 6. Mass air flow into apartments at different wind speeds and an inside/outside temperature difference of 20 K, for the **leeward** apartments with the mechanical ventilation system off.

Air flows into the apartments are slightly higher when the ventilation system is in operation. Figure 7 shows the air flows entering the apartments located on the windward side through the facade for different wind speeds when no stack effect is present.

t low wind conditions, infiltration is almost dependent of the height above ground. With gher wind speeds, we see that the infiltration ows follow the wind pressure profile.

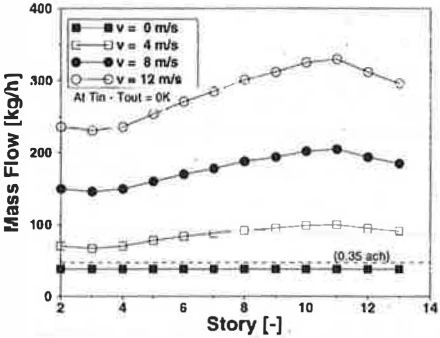

Figure 7. Mass air flow into windward apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system **on**.

CONCLUSIONS

In any study of a building as complex as a high-rise apartment it is important to verify the findings using as many techniques as possible. In the case of the Margolis we have been fortunate to have different data sources: leakage measurements, pressure tests and air infiltration measurements which have all been used to verify the model. Because comparisons between the model and measurement data agree well in several areas, such as similar directions and magnitude of pressure differences across apartment doors and stairwell doors, we have greater confidence in the simulation results.

Based on our analysis of the air flow simulations at Margolis we see that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled (pre-retrofit case), units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. Units facing the windward side were over-ventilated when the building experienced wind directions between west and north. At the same time, leeward side apartments would not experience any fresh air — air flows would enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. With the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments.

A fundamental issue here is the design question of how to best supply ventilation to individual apartments in a high-rise building. Using the corridor as the supply route has several challenges, including the control of the temperature of the supply air, the temperature of the corridor, the opening from the corridor to the apartment, and the balance between supply and apartment exhaust.

A major conclusion from our measurements and simulations is that each apartment has to be supplied with ventilation air directly. Pressure drops of the system have to be high enough to overcome natural forces to be able to ensure an even distribution of ventilation air. If ventilation air is supplied directly to the individual apartments, the apartments should be uncoupled from the rest of the building by tight apartment doors. This condition not only decreases the impact of natural forces on the distribution of ventilation air, but also reduces the disturbance to tenants of odors or noise from other apartments. In winter, supply air has to be preheated to avoid unpleasant cold drafts. Supply air provided by vents in the envelope should either be preheated by heating elements in the vent itself, or be supplied adjacent to heating sources. Ducted supply air should be preheated in the central unit.

On the exhaust side, studies have shown that when apartment occupants have local control over bathroom and kitchen exhaust, they use them less than one hour per day, if at all (Shapiro-Baruch, 1993), which makes it difficult to size the supply ventilation system. Continuous exhaust ventilation, however, presents the possibility of over ventilation and unnecessary use of energy.

Efforts to improve the energy efficiency of high-rise apartment buildings have been frustrated because of the lack of knowledge on air flows for individual apartments. Ventilation rates for individual apartments vary greatly due to height, orientation, and wind speed and outdoor temperature. Any recommendations for reducing air leakage will have to take these variables into account, so that efforts to tighten the shell for energy efficiency do not create health and comfort problems for the residents.

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