Diagnostics and Measurements of Infiltration and Ventilation Systems in High-Rise Apartment Buildings

Helmut E. Feustel and Richard C. Diamond, Lawrence Berkeley National Laboratory

The provision of ventilation air for high-rise multifamily housing has plagued retrofit practitioners and researchers alike. How does one determine whether sufficient levels of outdoor air are being provided to all apartments in a building? And how does one know whether the systems can be retrofit to improve their energy efficiency without compromising air quality? 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.

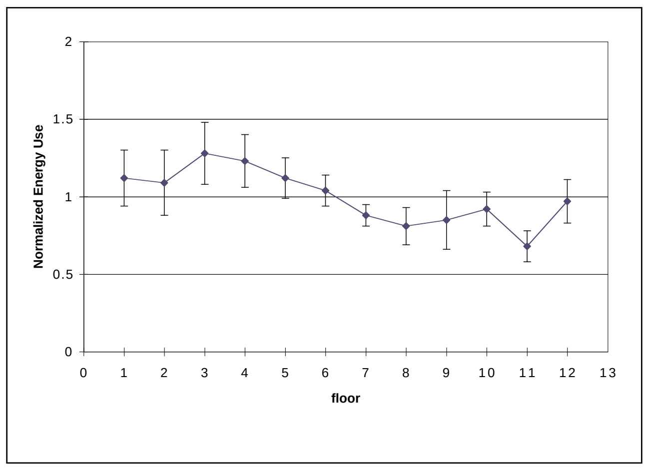
INTRODUCTION

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 1.

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—because of pressure differentials caused by inside-outside temperature differences. Air in the building rises up the vertical shafts (stairs and elevators) and draws in colder outdoor air at the base of the building. 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.

Figure 1. *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.*



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

BUILDING DESCRIPTIONS

We have focused our attention on three high-rise apartments buildings, all built around the same period and of similar size. One of the buildings is in Chelsea, Massachusetts and the other two buildings are in Oakland, California.

Margolis Apartments

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. There was mention of the windows being hard to open for some of the residents, both from the latching mechanism and the effort needed to lift the double-hung sash. No problems with condensation on the windows were reported since the retrofit. 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.

Westlake East and Westlake West

Westlake East was built in 1968 under the HUD 202 program of housing for the elderly and handicapped, and has 200 units, 158 studio and 42 one-bedroom apartments. The building is eleven stories and is of poured concrete bearing-wall construction. The apartments are heated by baseboard heaters supplied by hot water from boilers on the roof. The units have large sliding windows. Supply air is provided on each floor by individual units with heating coils and is designed to enter from the hallways under the apartment doors. The ventilation air is exhausted through the kitchen and bathroom registers. Four exhaust fans on the roof provide the exhaust air flows.

Westlake West was built in 1977 and has 13 floors. The building is of pre-cast concrete panels that were assembled on site. The apartments are heated by individual fan-coil recirculating units supplied by hot water from boilers assisted by solar collectors on the roof. There is a single air supply fan for the building that delivers air to each floor through a register in the hallway. The air enters the individual apartments through the 1/2″ gap under the apartment doors. The air is heated in winter and is at ambient temperature the rest of the year. The apartments have exhaust registers in the kitchen and bathroom, which are driven by 36 roof-mounted exhaust fans that operate 24 hours per day. The apartments have large sliding windows in the bedrooms and sliding doors onto the balconies.

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 (only at Margolis) under different weather conditions.

Air Leakage Measurements at Margolis

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.

By way of comparison, Kelley et al. (Kelly 1992) measured the air leakage pre-and post-retrofit in a high-rise apartment in Revere, Massachusetts, a few kilometers north of the Margolis apartment. They found an average pre-retrofit leakage for 17 of the apartments of 904 m^3/h at 50 Pascals, and a post-retrofit leakage of 763 m^3/h at 50 Pascals, a reduction of 15%.

With no difference in leakage areas before and after the retrofit we saw no change in the air flows, with an average at 50 Pascals of 1175 m^3/h pre-retrofit and 1185 m^3/h post-retrofit, a difference that was not statistically significant. In view of this lack of reduction in infiltration we were surprised that tenants who had previously complained of drafts were now satisfied. One explanation is that tenants were previously experiencing down drafts at the window due to cold surface temperatures, which no longer occur because of the new double-pane, low-e windows.

We also 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. Furthermore, the measurement technique being used is based on a reference pressure describing the pressure field around the building. In large buildings, it is very difficult to find a pressure point which acts as the reference pressure for the apartment being investigated. There is also the possibility that the measurement technique itself, i.e., depressurization with a blower door, temporarily seals the windows and distorts the findings.

Air Flow Measurements at Margolis

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 1996). This 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.

We measured the exhaust air flow from the kitchen hoods and the bathroom vents using a hot-wire anemometer. The filter area of the kitchen hood was divided into 5 sub-areas and an average velocity for each area was determined. From the air velocity, the flows were then calculated. The air velocity was also measured at several locations in the bathroom exhaust register.

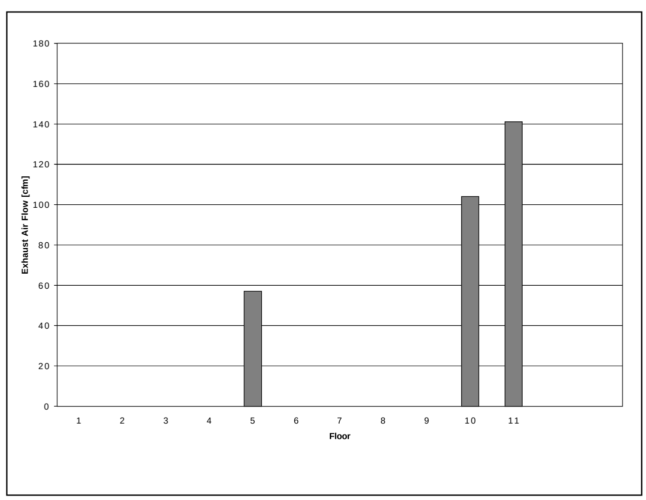
The exhaust flows of the seven apartments investigated showed the following characteristics: 1) air flow at the kitchen exhaust register with both the roof exhaust fan and the building supply on, but with the local exhaust fan off, ranged from 50 to 170 cfm, with a mean value of 92 cfm, significantly higher than the design value, (see Figure 2), 2) air flow at the bathroom exhaust register was smaller than the kitchen exhaust flows, and ranged from 40 to 86 cfm, with a mean value of 53 cfm, 3) With the addition of the local exhaust fan operating, kitchen exhaust flows reach values between 170 to 200 cfm (mean = 188 cfm) and, 4) the air flow at the bathroom register with the local bathroom fan operating (together with the roof top exhaust fan) produced 110 to 140 cfm (mean = 122 cfm).

Under normal operating conditions, i.e., the local bathroom and kitchen exhaust off, the total exhaust flow in the apartments would be between 100 and 260 cfm (mean = 145 cfm). The mean air flow supplied to the apartments from the corridor was measured at 22 cfm, so on average, under these weather conditions, the apartment would be drawing in an additional 120 cfm of outside air through the exterior wall and windows. This over-ventilation suggests the need for lowering the roof exhaust fan flow rates.

Temperatures, Pressures and Flows at Margolis

We measured the temperature of the supply air at the hallway registers for floors 2–13. They were all in the range of 28–30°C (83–86°F). These temperatures were higher than the setpoint in the energy management control system (EMCS) for the air supply, which is surprising, but in fact it serves as a more efficient strategy by providing air heated with the gas system than the individual electric units in the apartments and, it avoids cold drafts along the floor.

Figure 2. *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.*



We also measured the post-retrofit supply air flows at the hallway registers and they were all within a range of 900–1300 m^3/hr (530–760 cfm) 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 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.

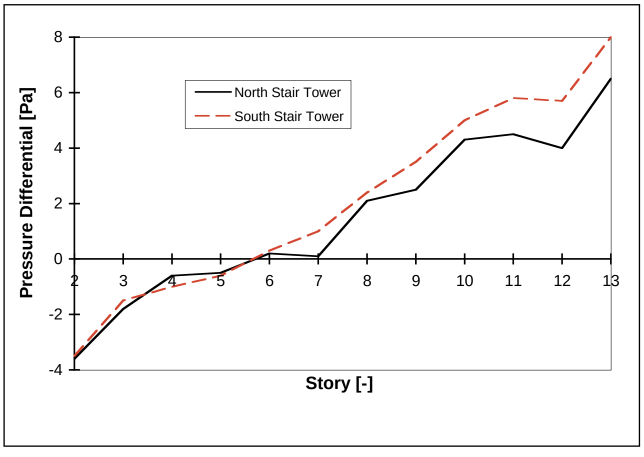
Inside the building, the air velocity from the elevator shaft into the corridor ranged from 2 m/s at the 13th floor down to 0.7 m/s at the 3rd floor. The temperature in the elevator was 19 ^{o}C (66°F) when the outside temperature was 7°C (45°F). The air velocity at the trash chute at the 13th floor, 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 (45°F) and the low wind speeds (Figure 3).

Ventilation Simulations at Margolis

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 at Lawrence Berkeley Laboratory, which calculates air flows based on mass balance calculations for individual zones (Feustel, 1990).

Figure 3. *Pressure differences between the stair towers and the hallways at Margolis.*



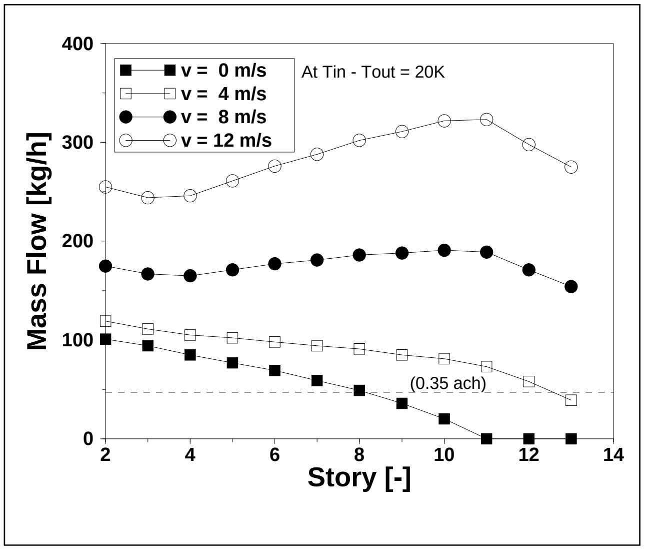
In order to limit the amount of input needed for the simulation model, each apartment was modeled as one zone, assuming the internal doors to be open. In order to account for the stack effect and the inter-zonal flows between the floors, all 13 floors were modeled.

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.

With a larger inside/outside temperature difference of 20 oC and zero wind speed, the air flow for the windward apartments decreases with height above ground from 83 m3/h (50 cfm) on the second floor to zero at the level of the 11th floor (Figure 4). With increasing wind speed the air

Figure 4. *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.*



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 5. 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.

Air flows into the apartments are slightly higher when the ventilation system is in operation. Figure 15 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. At low wind conditions, infiltration is almost independent of the height above ground. With higher wind speeds, we see that the infiltration flows follow the wind pressure profile.

Pressures and Airflows at Westlake East

The supply air flows, measured at the hallway registers using a flow-hood, ranged from 66–620 m3/hr (39–365 cfm) per floor, with the average, 330 m3/hr (195 cfm). This is below our rough estimate of the design specification for the supply air flow (Figure 7). There was a clear difference between

Figure 5. *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.*

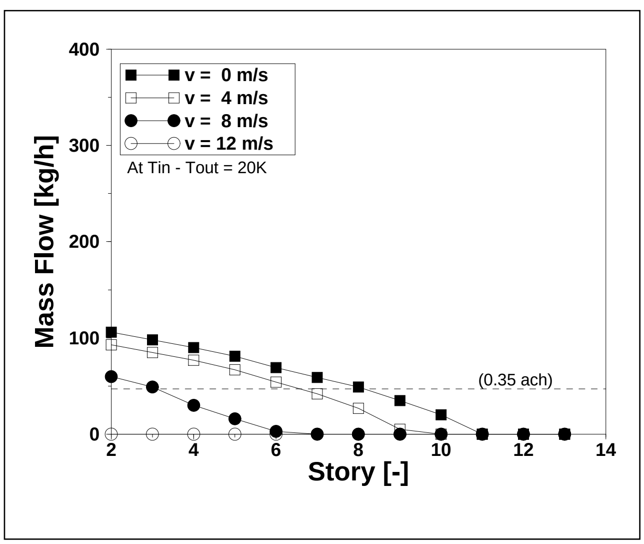


Figure 6. *Mass air flow into windward apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system* ***on.***

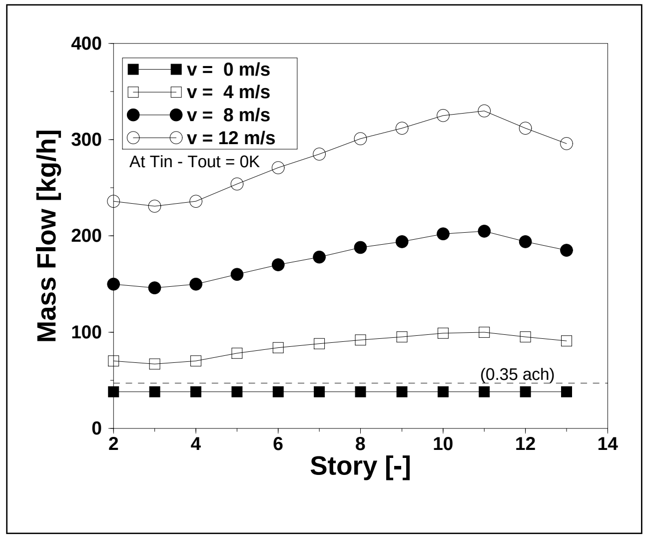
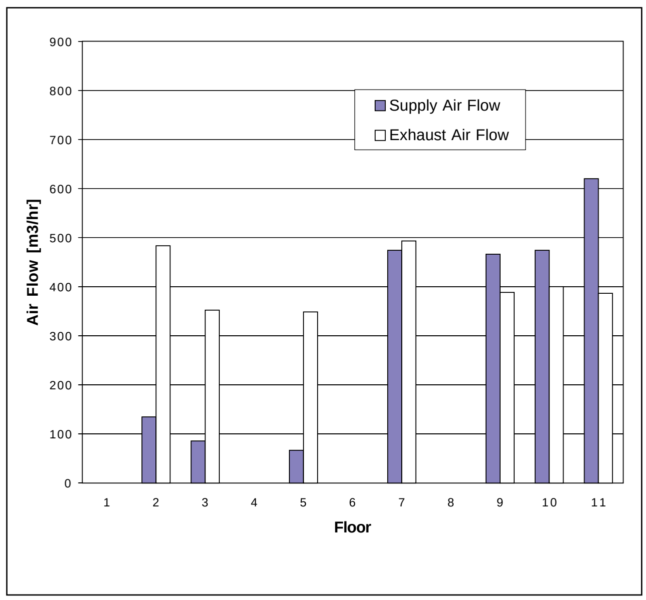


Figure 7. *Ventilation air flow, supply and exhaust, for Westlake East.*



the high flows on the upper floors (floor 7 and above) and the low flows on the lower floors (floor 5 and below), indicating that these systems are not operating correctly.

The exhaust air flows from the corridor were measured at different floors and the flows ranged from 350–490 m3/hr (205–290 cfm), averaging 410 m3/hr (240 cfm). Because the exhaust flows on the lower floors were often higher than the supply flows, there was not much possibility for supply air to reach the apartments. Most of the air supplied at one end of the hallway was exhausted directly out the other end.

In the East building we observed that a recent weatherstripping of the apartment doors blocked the path for the supply air. One of the residents noted ‘‘that we used to get plenty of air—now we get nothing.’’ It was evident from the discussions with residents that very few were aware of the door slot as the source of ventilation air. Residents indicated that they keep their windows open, often year round. The weatherstripping was installed when tenants complained of cold drafts from the hallway—which were likely due to the unheated supply air after the supply-air heaters failed.

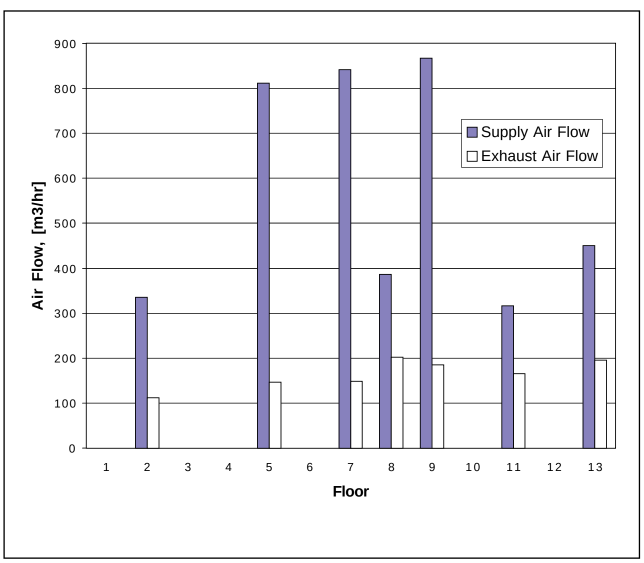
Pressures and airflows at Westlake West

The supply air flows, measured at the hallway registers using a flow-hood, ranged from 320–870 m3/hr (190–510 cfm) per floor, with the average, 570 m3/hr (340 cfm), below our estimate of the design specification for the supply air flow (Figure 8).

If we assume 16 apartments per floor, and the ASHRAE 62 standard for ventilation of 15 cfm per person, then we would need 480 cfm per hallway (assuming double occupancy) if all the supply air were reaching the apartments. We know, however, that this is not the case, due in part to the exhaust air from the garbage chute rooms and the air flow to the elevators. And while the average supply air flow (340 cfm) was below the ASHRAE standard, several of the floors had much higher flow rates that would meet this standard.

The 1/2″ undercut beneath the apartment doors appears sufficient for the supply air flow, but we noted several cases

Figure 8. *Ventilation air flow, supply and exhaust, for Westlake West*



where the occupants block this gap, with towels, rugs, or other objects. The reasons offered by the residents for blocking this gap were ‘‘to block the hallway light’’ ‘‘to prevent noise’’, ‘‘I don’t know, we just do it’’, ‘‘to keep out the cockroaches—although they aren’t a problem anymore’’ and ‘‘to keep out the cooking smells.’’

The exhaust air flows from the corridors were measured at different floors, and the flows ranged from 66 to 119 cfm, averaging 97 cfm. Little leakage was noticed between the corridors and the stairwells because of the good weatherstripping on the stairwell doors. Leakage to the elevator shaft was not measured, but we observed that the openings from the elevator shaft to the penthouse were minimal. We did observe significant airflow into the hallway on the upper floors.

Air Leakage Measurements at Westlake East & Westlake West

We made air leakage measurements using a single blower door on four apartments, two in each building. Because the buildings were concrete construction, we assumed that there would be little air flow between apartments. The wind speeds were very low during the morning measurements in the West building, and while the wind picked up in the afternoon, we were still able to make reasonable measurements in the East building as well.

East Building: The two East building apartments are 49 m2 and 34 m2 (490 and 340 ft2) in floor area, with volumes of 117 m3 and 82 m3 (3930 and 2730 ft3). The two apartments (#1015 and #503) had air flows at 50 Pascals pressure difference of 445 and 416 m3/hr (260 and 245 cfm) respectively. This is roughly 4 air changes per hour at 50 Pascals, and represents tight construction. This was not surprising given that this was a poured concrete building. With the sliding windows taped at the joints, the leakage was reduced 3–13%. The exhaust registers when untaped added another 35–50%.

West Building: The two West building apartments are roughly twice the floor area of the East building apartments, both 52 m2 (520 ft2) in floor area, with a volume of 125 m3 (4165 ft3). The two apartments (#826 and #1134) had air flows at 50 Pascals pressure difference of 1089 and 1038 m3/hr (640 and 610 cfm) respectively, which corresponds roughly to 8 air changes per hour at 50 Pascals, which is relatively tight construction. With the sliding windows and balcony doors taped at the joints, the leakage was reduced roughly 10%. The exhaust registers when untaped added another 10%. The large access panel to the plumbing chase added another 10%.

CONCLUSIONS

In any study of a building as complex as a high-rise apartment it is important to validate the findings using as many techniques as possible. In the case of the Margolis and Westlake Apartments we have been fortunate to have different data sources: leakage measurements, pressure tests and air infiltration measurements which have all been used to validate 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 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.

ACKNOWLEDGMENTS

We would like to thank Bob Nason and the staff of the Chelsea Housing Authority, John Jordan and the staff of Westlake Christian Terrace, Larry Bravo and John Snell, EUA/ CCS & Citizens Conservation Corporation, Michaela Abraham from Oak Ridge National Laboratory, Richard Karney and Michael Myers, US DOE. Lastly, we would like to thank the residents of the Margolis and Westlake Apartments for their cooperation in allowing us to take the measurements in their homes.

This works was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Systems Division, of the U.S. Department of Energy, under contract DE-AC03-76SF00098.

REFERENCES

Diamond, R.C., H.E. Feustel, and D.J. Dickerhoff. 1996 ‘‘Ventilation and Infiltration in High-Rise Apartment Buildings,’’ Lawrence Berkeley Laboratory Report, LBL-38103, Berkeley, California.

Feustel, H.E. and A. Raynor-Hooson. 1990. ‘‘Fundamentals of the Multizone Air Flow Model COMIS,’’ Technical Note TN 29, Air Infiltration and Ventilation Centre, Bracknell, UK.

Kelly, Mark E., McQuail, John E., and O’Brien, Robert. 1992. ‘‘Case Study of Ventilation Improvements in a Multifamily Building,‘‘ in the Proceedings of the 1992 ACEEE Summer Study, vol. 2, American Council for an Energy-Efficient Economy, Washington DC, 1992.

Shapiro-Baruch, Ian. 1993. ''Evaluation of Ventilation in Multifamily Dwellings,'' New York State Energy Research and Development Authority, Albany, New York, Report 93-5.