# Modeling Ventilation in Multifamily Buildings

*John Markley and Curtis Harrington, UC Davis Western Cooling Efficiency Center*
*Garth Torvestad, Benningfield Group, inc.*

## ABSTRACT

Proper ventilation is an essential component of multifamily building design due to its effects on occupant health and comfort. Though the concept of providing fresh air is straightforward, multifamily buildings pose several unique challenges that require special consideration in order to avoid excessive ventilation and energy waste. Two issues in particular that must be addressed in multifamily buildings are minimizing the air that moves between tenant spaces and ensuring that each individual space receives the required ventilation. In an effort to address these topics the UC Davis Western Cooling Efficiency Center, as part of a Public Interest Energy Research project, evaluated potential improvements to mechanical ventilation of multifamily buildings. This paper outlines the results from energy models of several multifamily building configurations to improve airflow balancing and energy efficiency in high-rise multifamily buildings with central shaft exhaust ventilation.

The findings support several recommended changes to California's energy code:

1) All residential ventilation requirements should be unified under a single standard to remove discrepancies between high-rise and low-rise buildings as a result of the misalignment of ASHRAE Standard 62.1 and ASHRAE Standard 62.2
2) Air tightness requirements should be implemented for the building envelope between interior spaces to reduce the transfer of contaminated air between tenants
3) For buildings that employ central ventilation systems:
    3a. Air tightness requirements should be implemented for central ventilation ducts
    3b. Pressure independent grills/dampers should be required for central ventilation systems

## Introduction

Multifamily buildings are a unique and common class of structure with specialized design demands and distinctive energy use profiles. Historically multifamily buildings have fallen between commercial and residential jurisdictions and, as a result, they have been addressed in a piecemeal fashion resulting in a hodgepodge of codes and standards that govern their construction and operation. Due to this lack of focus many of the unique characteristics of multifamily buildings are either unaddressed or forced to adhere to guidelines that were developed for entirely different purposes.

## Background

In 2010 The California Energy Commission set out to improve the manner in which California's Building Code[1] approached multifamily buildings by sponsoring a Public Interest

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[1] California's Building Energy Efficiency Standards: Title 24, Part 6

Energy Research (PIER) project called Unique Multifamily Code-Relevant Measures (UMCRM). One particular focus of the UMCRM project was to evaluate the opportunities and possible solutions surrounding ventilation in multifamily buildings with an eye toward achieving California's goal of net-zero building design by 2020.

Like many states California's ventilation codes are founded upon the work of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) which initiated and authored the preeminent ventilation standard in North America, ASHRAE Standard 62.[2] Originally, ASHRAE 62 was developed with a focus on commercial applications and did little to address issues specific to single family residences. Around the year 2000, ASHRAE introduced Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings effectively splitting Standard 62 into two separate documents (Sherman, 2000).

As defined by ASHRAE, Standard 62.1 addresses ventilation issues in "all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade, vehicles, and aircraft." Alternatively, ASHRAE 62.2 addresses ventilation issues in "single-family houses and multifamily structures of three stories or fewer above grade, including manufactured and modular houses".

## High-Rise vs. Low-Rise Multifamily Ventilation Rates

As you can see by the previous descriptions, multifamily buildings fall under both standards divided only by the number of stories above grade.[3] More to the point, high-rise multifamily buildings governed by Standard 62.1 have had requirements imposed upon them that were developed for commercial purposes. The requirements are laid out in Table 1 for each building type.

Table 1. Ventilation rate requirements for low-rise (ASHRAE 62.2) and high-rise (ASHRAE 62.1) buildings

| Building Type | Requirement Type | Requirement | Units |
|---|---|---|---|
| Low-Rise Multifamily (ASHRAE 62.2) | Whole Building, $Q_r$ | $0.03A + 7.5(N_{br} + 1)$ | CFM |
| High-Rise Multifamily (ASHRAE 62.1) | Dwelling Unit | $5P + 0.06A$ | CFM |
| | General Minimum | $15P$ | CFM |
| | Common Corridors | $0.06A$ | CFM |

In an effort to illustrate the differences between how ventilation rates outlined in Table 1 are calculated, Table 2 shows several representative scenarios and configurations for the various inputs and Figure 1 plots the ventilation rate of each calculation method vs. the floor area.

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[2] The complete title of the document is "ASHRAE 62: Ventilation for Acceptable Indoor Air Quality"

[3] Three stories and fewer is classified as "Low-Rise" while four stories and more is classified as "High-Rise"

Table 2. Ventilation rate calculations for representative low-rise and high-rise multifamily buildings per ASHRAE 62.2 and ASHRAE 62.1, respectively

| Area (ft$^2$), [$A$] | # of Bedrooms, [$N_{br}$] | Low-rise ventilation rate: $0.03A + 7.5(N_{br} + 1)$, [CFM] | High-rise dwelling unit ventilation rate: $5 \cdot (N_{br} + 1) + 0.06 \cdot A$, [CFM] | Ratio of High rise vs. low rise |
|---|---|---|---|---|
| 500 | 1 | 30 | 40 | 1.3 |
| 1000 | 1 | 45 | 70 | 1.5 |
| 1500 | 2 | 67.5 | 105 | 1.5 |
| 2000 | 3 | 90 | 140 | 1.5 |
| 2500 | 4 | 112.5 | 175 | 1.5 |
| 3000 | 5 | 135 | 210 | 1.5 |

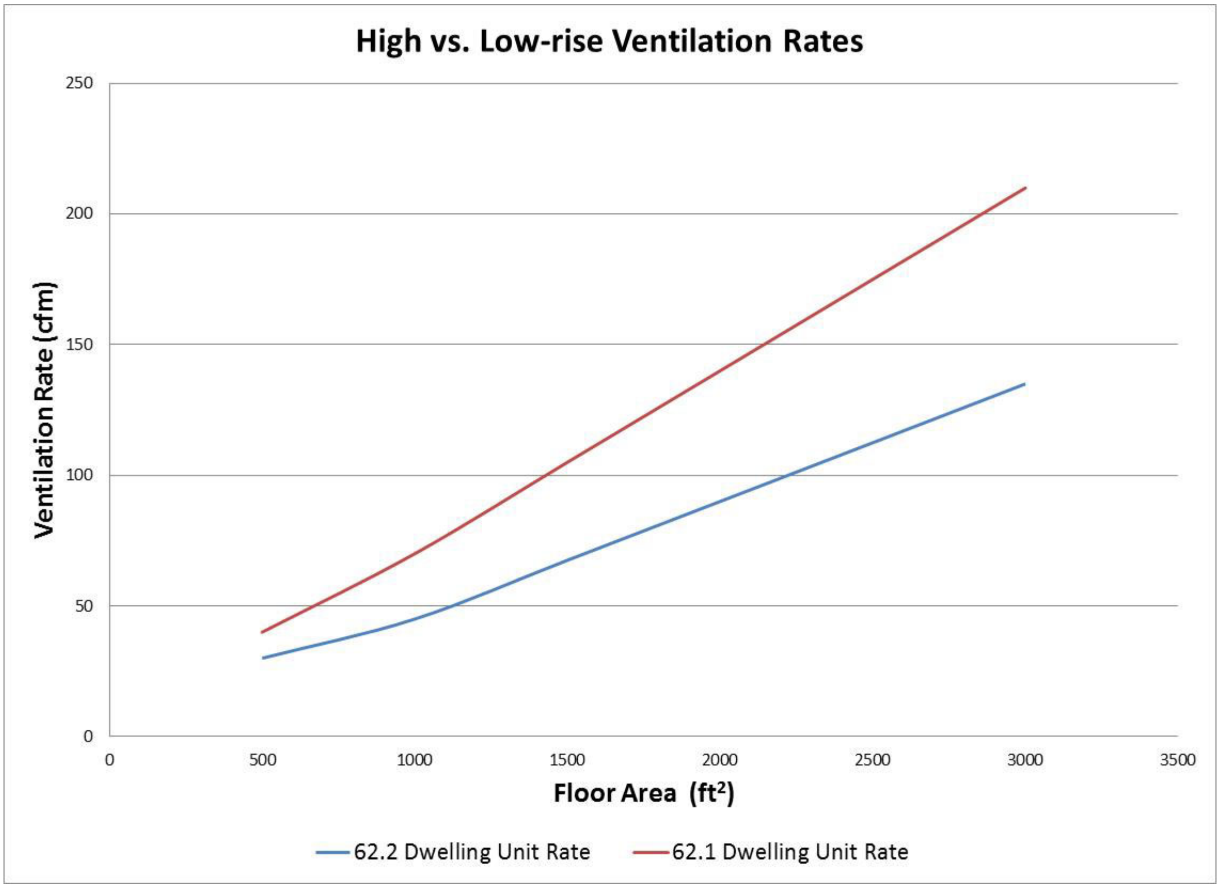

Figure 1. Comparison of low-rise and high-rise ventilation rates calculated in Table 2.

Figure 1 illustrates a clear difference between ventilation rate requirements for high-rise and low-rise buildings. Thus, in order to comply with these standards, for a similar size dwelling unit, high-rise buildings must have a significantly higher ventilation rate than low-rise buildings. Multifamily buildings are especially impacted by this discrepancy since two seemingly identical buildings, which may only differ by one story, have unique sets of requirements enforced on them leading to ventilation rates that can differ significantly.

## Moving Toward Common Ventilation Requirements

In recent years the ASHRAE 62.2 standard has made a significant and sustained effort to focus on the specific needs of multifamily buildings. Two of the most significant areas garnering recent attention are the removal of infiltration credits built into the residential calculations and reducing individual compartment envelope leakage, termed compartmentalization. The split between high-rise and low-rise buildings, however, continues to persist.

The move toward removing the amount of infiltration credits for multifamily buildings was due to the recognition that much of the infiltration in multifamily units can and will enter the compartment through shared wall space. As such, infiltration from a neighboring space should clearly not be counted toward the necessary ventilation that a low-rise multifamily dwelling unit experiences because air coming from a neighboring space is often contaminated[4] and can include chemicals ranging exhaust from garages to tobacco smoke from other tenants. In addition, because transfer air is often undesirable, unnecessarily high exhaust requirements can reduce indoor air quality that can result in larger and larger portions of contaminated air being pulled from adjoining spaces.[5]

In addition to removing infiltration credits the process of reducing envelope leakage of the individual compartments (compartmentalization) is an effort to make it ever more difficult for air to transfer between occupied spaces; as stated by ASHRAE 62.2 "measures shall be taken to reduce inter-apartment airflows to less than 0.2 cfm/ $ft^2$ at 50 Pascal through better sealing of common walls, ceilings, and floors." Furthermore, reducing the air permeance of the individual compartments and the associated reduction in infiltration saves energy by reducing the amount of conditioning load required to attain a comfortable indoor environment.

## Challenges in Achieving Proper Ventilation in Multifamily Buildings

Accurately and dependably achieving the required amount of ventilation can be quite a difficult endeavor, especially in high-rise buildings that are typically more susceptible to environmental forces. Factors that work against consistent ventilation include the temperature difference between inside and outside (i.e. stack effect), wind, and opening a door in a stairwell. All of these factors influence the pressure profile of a building and directly affect the performance of the ventilation system.

In addition to environmental and operational considerations, the architectural attributes, such as service chases[6] and penetrations, can play a large role in how air moves through a building. Further, if the ventilation system employs a central shaft (vs. individual spot exhaust) that serves several floors, the additional air pathways influence the pressure profile of the building. Therefore, central shaft ventilation systems are particularly susceptible to changing environmental conditions and balancing such a system is an exercise in futility because there are so many variables; even if one were to succeed in manually manipulating dampers etc. to achieve balanced and even airflow through all of the ventilation registers in a central ventilation system the conditions will soon change and the system can become out of balance.

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[4] Outdoor air can also contain undesirable levels of similar pollutants such as vehicle exhaust particulate matter, ozone, $NO_2$, etc.

[5] Air moving between tenants in a multifamily building can also be referred to as "transfer air".

[6] Any pathway between floors intended for plumbing, electrical, or mechanical service.

The combination of varying environmental conditions and a central exhaust system leads to two bounding scenarios 1) if the minimum required ventilation is achieved at the grille with the lowest flow, there is a significant amount of waste occurring in the form of over ventilation at the other grilles in the system 2) if the minimum required ventilation is barely achieved at the grille with highest flow, there is a significant amount of under ventilation at the other grilles in the system. In practice central shaft systems typically fall somewhere in the middle where over ventilation and energy waste occur in part of the system while under ventilation, leading to potentially inadequate indoor air quality, occurs in other parts of the system.

Compounding the problems caused by stack effect, leaks in the central shaft require increased fan flow to provide the designed flow rate at the exhaust register of a space. The further down the exhaust shaft, the more air is pulled through leaks rather than the intended exhaust registers. Both stack effect and leaks in ducts contribute to excess fan energy use and/or inadequate ventilation.

## Modeling and Simulation of Ventilation in Multifamily Buildings

The goal of this research was to assess the impact of various mitigation strategies to the challenges faced with multifamily ventilation systems, and more specifically high-rise central exhaust systems. Since part of the proposed code change involves unifying all multifamily ventilation rates by reducing high-rise ventilation rates to those outlined by ASHRAE 62.2 for low-rise multifamily buildings, the importance of achieving the proper ventilation rate throughout high-rise buildings is even more important. The strategies evaluated include: sealing exhaust ducts, installing self-balancing dampers at each exhaust grille, and sealing each individual apartment envelope.

### Model Description

A representative multifamily apartment building was modeled in EnergyPlus to investigate the impact that various ventilation-related code changes, technologies, and construction practices have on energy use and ventilation airflows. Although Department of Energy reference models exist for multifamily buildings, there is no multifamily reference model available that uses the airflow network objects in EnergyPlus that allow stack, wind, and interior air flows to be calculated on an hourly bases. Therefore, the model discussed here was developed specifically for this study. The EnergyPlus model was simulated in several California Climate Zones including 3 (San Francisco Bay area), 8 (Los Angeles area) and 12 (Sacramento area), to account for variations in climate.

Figure 2 illustrates the floor plan developed for this study, which is symmetrical in order to minimize the effects that building orientation may have on the simulated results. Building materials were chosen primarily from the National Renewable Energy Laboratory's (NREL) Building Component Library, which provides physical properties for a range of construction types. Title 24 compliant constructions were used for all elements of the building envelope. In typical apartment construction, interior walls are not insulated and interior doors are not designed to seal individual rooms in an apartment. Therefore, individual rooms in each apartment are not significantly isolated from each other and were considered to be part of one well-mixed thermal zone.

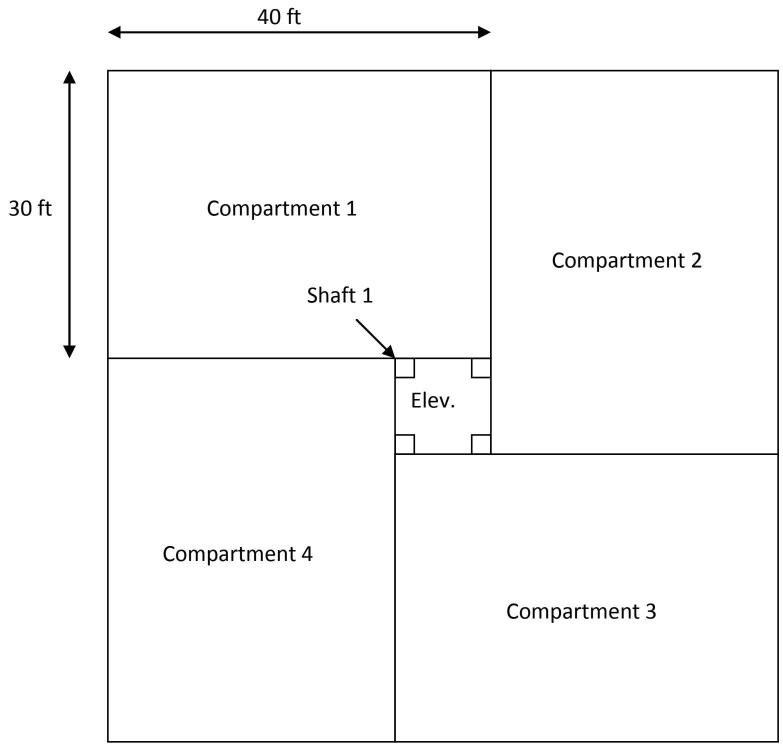

Figure 2. Floor plan description used in the energy models.

Another limitation presented by using the airflow network objects in EnergyPlus is that the typical forced air heating and cooling systems used in multifamily buildings could not be modeled simultaneously with the ventilation system. Therefore, heating and cooling loads were satisfied using a radiant hydronic system fed by a central plant providing hot and cold water. Conditioning of each apartment was individually controlled by a thermostat whose setpoint schedules were configured using a temperature profile specified by the Energy Commission's Residential Alternative Calculation Method (ACM) (CEC 2008) Manual. Building internal mass and internal gains were also set according to the ACM manual.

To capture the effects of distributed leak heights on airflow, all exterior walls for each apartment were modeled with three leaks evenly spaced along the height of the walls. Interior walls, which are not directly impacted by wind or stack effect (because temperature differences between indoor zones are small), were modeled with a single leak between each compartment. Floors and ceilings were each modeled with a single leak in each surface because height is not a factor in horizontal surfaces.

To account for vertical air movement the model includes an elevator shaft in the common space adjoining all apartments on each floor. Each apartment was modeled with a leak through the apartment door and another leak through the elevator door. The leak area around the door leading to the elevator shaft, as well as the leak through the elevator door (ceiling leak in modeled elevator shaft), was based on measured data from a high-rise residential building (Jae-Hun et al. 2005).

The effect of compartmentalization was modeled by sealing exterior and unit-to-unit leaks to the level specified in ASHRAE 62.2 (0.2 CFM50/sqft of total envelope area[7]) from a

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[7] Total envelope area refers to the sum of all floor, ceiling and wall areas.

baseline leakage (0.4 CFM50/ft$^2$ of total envelope area). The distribution of leaks was determined using various sources. The floor/ceiling leakage was calculated based on typical leakage for floors of commercial buildings (ASHRAE 2009), which assumes that high-rise multifamily buildings have similar floor construction to similarly sized commercial buildings[8]. The remaining leakage needed for the unit to meet the total specified envelope leakage area was distributed between interior and exterior walls. The door leak was subtracted from the previously determined total interior leakage, and remaining interior leakage was distributed among interior wall surfaces.

Three types of mechanical exhaust ventilation systems were modeled in this study:

- Central shaft exhaust with a rooftop fan and unbalanced registers at each apartment,
- Central shaft exhaust with a rooftop fan and self-balancing dampers at each apartment, and
- Individual unit exhaust fans.

In addition, two methods for sizing the rooftop fan were used: 1) a prescriptive approach in which the fan size was based on the sum of ventilation airflow requirement for all units served[9], and 2) a compliant approach in which the fan size was based on the airflow needed for all apartments served to receive the minimum required ventilation rate during most hours of the year. The second approach accounts for the variable, unbalanced, apartment-level airflows known to exist in many multifamily buildings[10], as well as the duct leakage present in the system.

## Modeling Scenarios

The various models that were developed to evaluate the various ventilation schemes are described in Table 2. Table 3 outlines the independent variables used as inputs for each respective simulation.

Table 3. Ventilation systems and schemes modeled and evaluated

| Ventilation Schemes Modeled | Description |
|---|---|
| Central shaft without balancing | Central shaft exhaust ventilation systems with equivalent sized grille openings |
| Central shaft with balancing | Central shaft exhaust ventilation systems that had been manually balanced once during the year by adjusting the grille openings |
| Central shaft with self-balancing dampers | Central shaft exhaust ventilation systems with self-balancing dampers installed at each grille |
| Individual unit | Individual unit ventilation with a fan installed in each apt |

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[8] Stakeholders, including consulting engineers and contractors interviewed, have not indicated any difference in the construction practices of similarly sized multifamily and commercial buildings.

[9] The prescriptive approach is believed to be standard industry practice.

[10] The method assured that the average ventilation for each room was at least one standard deviation above the minimum required ventilation requirement.

Table 4. Independent variables used in the models

| Variables Simulated | High-Rise | Low-Rise |
|---|---|---|
| Ventilation Rate | 92 CFM per unit | 66 CFM per unit |
|  | **Leaky** | **Tight** |
| Duct Leakage | 25% of fan flow | 5% of fan flow |
| Compartmentalization | 0.4CFM50/ft$^2$ envelope area | 0.2CFM50/ft$^2$ envelope area |

## Simulation Results

The results of the simulations are presented and analyzed based on two primary metrics: 1) ventilation performance (i.e., stability and distribution of ventilation flow rates), and 2) building energy use. In all cases the overall energy consumption of the building was reduced compared to a baseline condition that satisfies ventilation requirements throughout the building; interestingly, however, nearly all cases show a small increase in the cooling load that is usurped by large heating energy savings. As expected the location (i.e. weather) has a large impact on the overall energy consumption of the buildings.

Figure 3 shows the average exhaust flow each of the six floors for four of the model scenarios with the blue line indicating the target ventilation rate for each of the models. The compliant model with no balancing shows significant over ventilation on average during the year. This results in wasted energy in the form of fan energy, but primarily heating and cooling energy to condition the extra ventilation air. The prescriptive model with no balancing shows significant under ventilation on average, which is assumed to result in inadequate indoor air quality. When balancing the prescriptive model once in the summer, the ventilation flow distribution improves but still shows that many floors are under ventilated. The model with self-balancing dampers demonstrates very steady ventilation flows throughout the year providing each floor with the minimum ventilation required without any significant over ventilation.

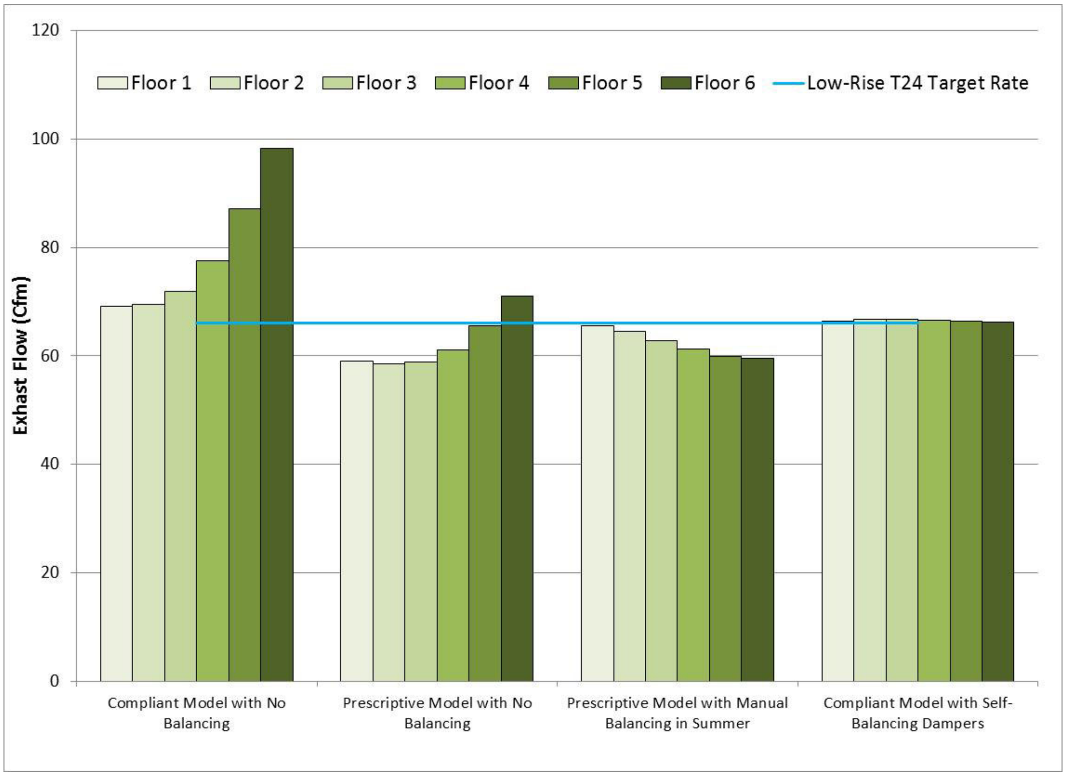

Figure 3. Average exhaust flow rate for apartments on each of the six floors for four of the models simulated (CZ12).

Figure 4 shows the average amount of transfer air that enters an apartment on each floor of the building for California Climate Zone 12 (Sacramento Area). This is the average result for all models with leaky envelopes (on left side) and tight envelopes (on right side). Figure 4 clearly illustrates that tighter construction practices result in less transfer air entering the apartments. Ultimately, this suggests an improvement in indoor air quality since less make-up air comes from neighboring spaces. Though the reduction of the amount of air coming from adjacent spaces is improved, a significant fraction of the air exhausted still originates from other apartments.

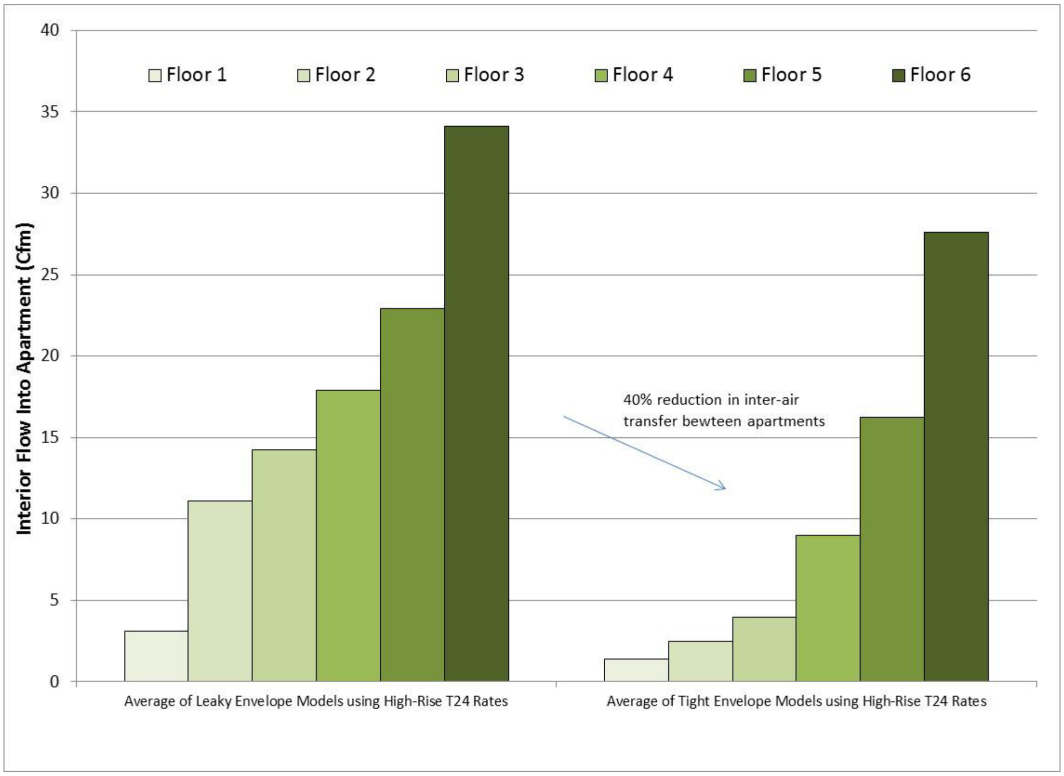

Figure 4. Average interior air flow into apartments on each floor for models with leaky vs. tight envelopes (CZ12).

Figure 5 illustrates the average reduction annual energy resulting from lowering the high-rise ventilation rate to the same rate required in low-rise buildings. The percent reduction in annual energy use was found to be 38% for California climate zone 3, 20% for California climate zone 8, and 29% for California climate zone 12. Reducing the amount of leakage each compartment experiences from "leaky" envelopes (Ueno, Lstiburek, and Bergey 2012) to "tight" envelopes[11] shows a similar trend in the reduction of annual energy across the same California climate zones, see Figure 6. Although the percentages for annual energy savings are not as significant compared to reducing high-rise ventilation rates it is encouraging to observe that the net effect of compartmentalization saves energy; the primary benefits of compartmentalization are improving indoor air quality by reducing transfer air by 40% as previously discussed.

For central shaft systems, the effect on annual energy use of reducing duct leakage from 25% of total flow to just 5% (ASHRAE 2013) of total flow is shown in Figure 8. The percent reduction in annual energy use was found to be 23% for California climate zone 3, 13% for California climate zone 8, and 16% for California climate zone 12. In addition to these annual energy savings, and perhaps more important to the overall goal of reliably achieving proper ventilation, sealing central ventilation shafts allow self-balancing dampers to operate much more effectively (Ueno, Lstiburek, and Bergey 2012).

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[11] The value for "tight" envelopes 0.2cfm/ft$^2$ of envelope area is the minimum proposed by ASHRAE standard 62.2 and would show greater savings for values tighter than the minimum requirement.

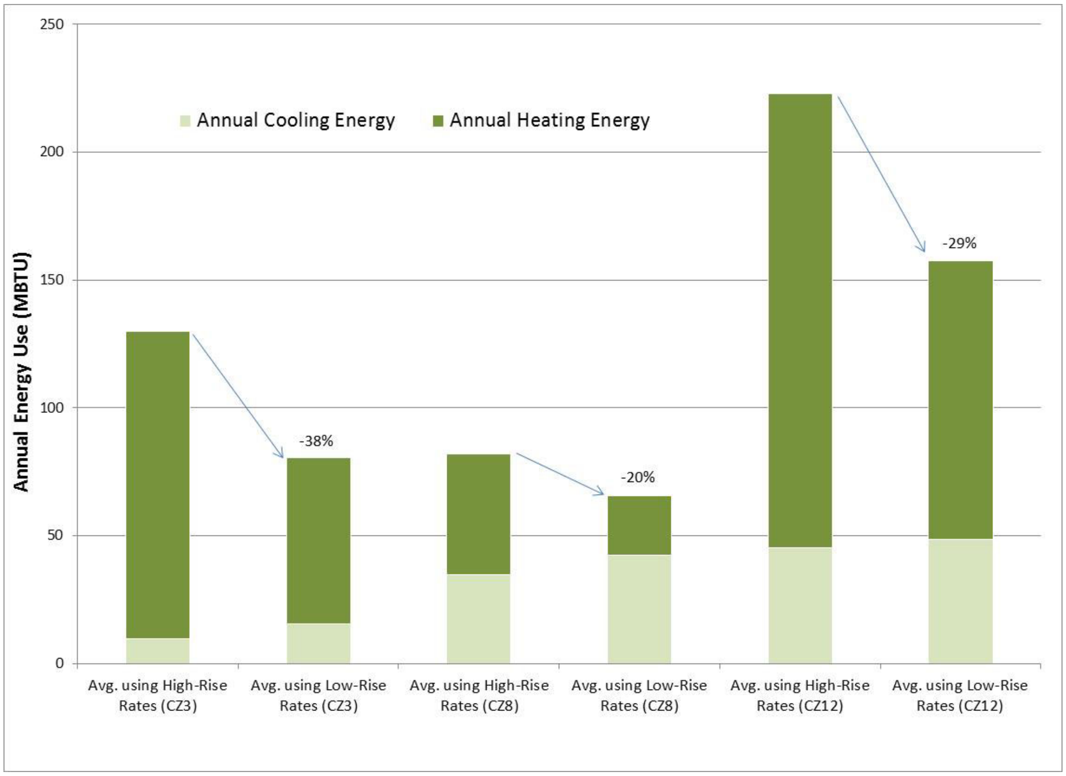

Figure 5. Comparison of annual energy use between low-rise and high-rise ventilation rates across California climate zones 3, 8, and 12.

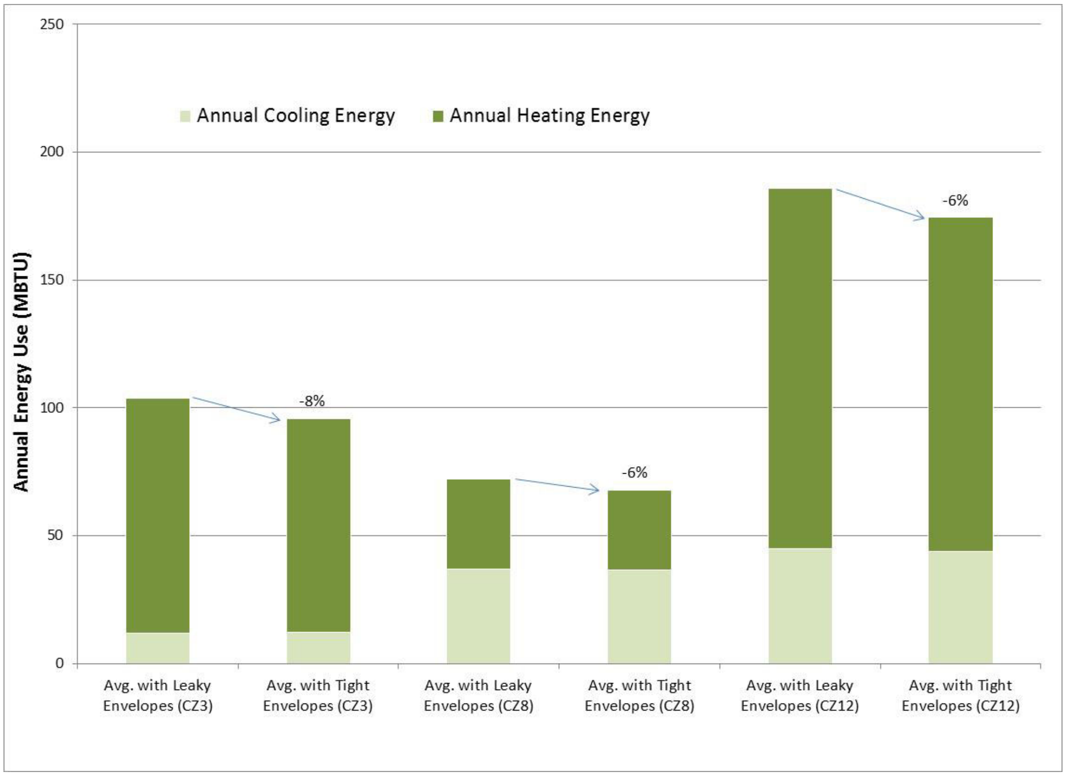

Figure 6. Comparison of annual energy use between “leaky” envelopes (0.4cfm/ft$^2$ of envelope area) and “tight” envelopes (0.2cfm/ft$^2$ of envelope area) across California climate zones 3, 8, and 12.

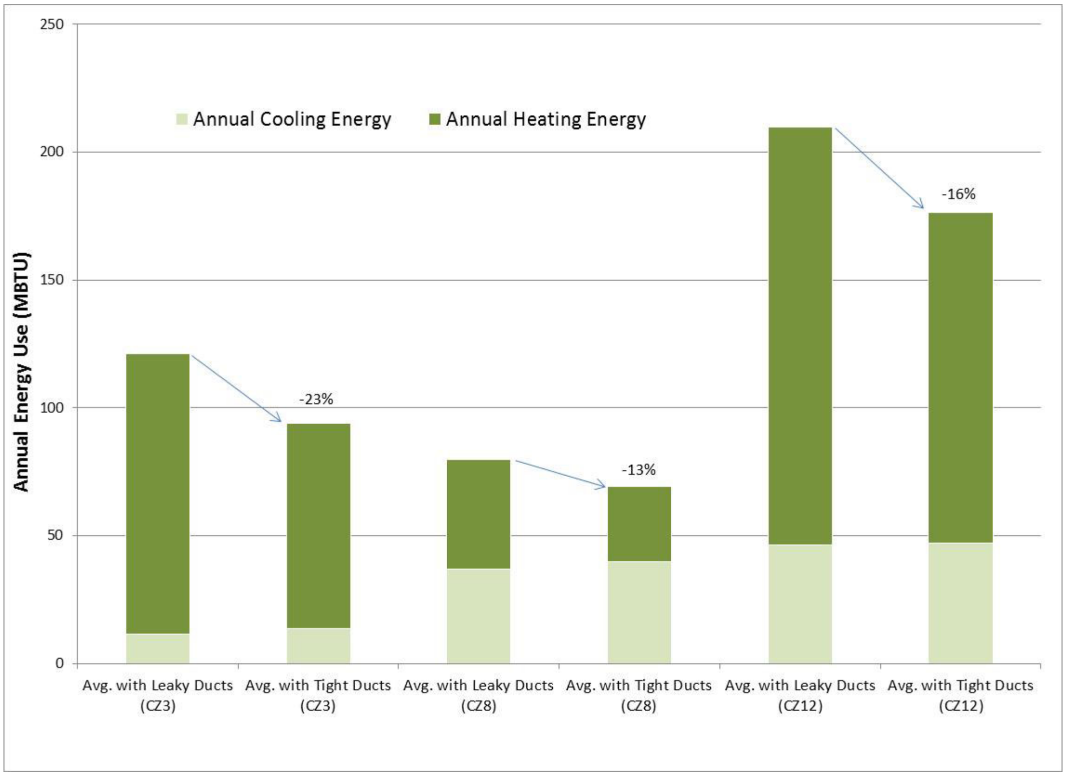

Figure 7. Comparison of annual energy use between “leaky” ducts (25% of total flow) and “tight” ducts (5% of total flow) across California climate zones 3, 8, and 12.

Lastly, a building that combines lowering ventilation rates, tightening compartment envelopes, tightening central shafts, and using self-balancing dampers was compared to three different “baseline” cases. The first baseline comparison consisted of a building using a central ventilation shaft with high-rise ventilation rates that were achieved in even the least favorable instances (i.e. compliant), leaky envelopes, and leaky ducts. The second baseline comparison was identical to the first case except that the value of electricity and gas were input according to California’s Time Dependent Valuation (TDV) methodology. The third and final baseline comparison consisted of a building using a central ventilation shaft with high-rise ventilation rates that were achieved on average (i.e. prescriptive), leaky envelopes, and leaky ducts. The results of these comparisons are presented in Table 4.

Table 5. Annual energy savings (%) of all ventilation measures combined compared to several baselines

| | CA Climate Zone 3 | CA Climate Zone 8 | CA Climate Zone 12 |
|---|---|---|---|
| Compliant | 70% | 52% | 59% |
| TDV | 39% | 8% | 31% |
| Prescriptive | 35% | 13% | 28% |

## Time Dependent Valuation

The multifamily ventilation improvements that were modeled result in significant energy savings for high-rise multifamily buildings across multiple California Climate Zones. Yearly savings estimates were based on results of the EnergyPlus model described above in the paper and assume all measures were adopted. The TDV values weight the value of energy saved based on the value of energy at every particular hour of the year. This analysis is based on a 30-year life cycle. A complete analysis across multiple building prototypes and all climate zones, weighted for the population of buildings has not yet been completed. The analysis looking at three critical climate zones shows significant savings (Table 5).

Table 6. Energy savings and TDV savings due to adopting the code changes in each Climate Zone modeled

| | | Electricity Savings (kWh/yr) | Natural Gas Savings (Therms/yr) | TDV Electricity Savings (TDV kBTU) | TDV Gas Savings (TDV kBTU) | **TDV Net Savings (TDV kBTU)** |
|---|---|---|---|---|---|---|
| **CZ3** | **Per six-story multifamily Building** | -689 | 1,749 | -31,981 | 88,881 | **56,900** |
| | **Savings per square foot** | -0.024 | 0.061 | -1.110 | 3.086 | **1.976** |
| **CZ8** | **Per six-story multifamily Building** | -1,050 | 816 | -30,263 | 42,944 | **12,681** |
| | **Savings per square foot** | -0.036 | 0.028 | -1.051 | 1.491 | **0.440** |
| **CZ12** | **Per six-story multifamily Building** | -114 | 2,048 | 1,568 | 106,608 | **108,176** |
| | **Savings per square foot** | -0.004 | 0.071 | 0.054 | 3.702 | **3.756** |

For the purposes of calculating the Time Dependent Valuation (TDV) the baseline model represents a building that meets the intent of the 2008 Title 24 standard using standard practices for mechanical ventilation system design and installation. This model is a central shaft model without balancing with leaky ducts and leaky envelopes, and used the compliant approach to sizing the fan.

## Conclusions

This paper presented the results of several EnergyPlus simulations of showing the impact of multiple proposed changes to California's Title 24 Building Codes. The proposed changes are intended to improve ventilation in multifamily buildings by unifying the ventilation code under a unique set of requirements for multifamily buildings, requiring that self-balancing dampers be installed on each grille and duct leakage be reduced to 5% of fan flow when using central shaft ventilation systems, and require that all apartments are sealed to the ASHRAE 62.2 recommended 0.2 CFM50/ft$^2$ of envelope area. The models show that adopting these changes not only improve indoor air quality but also reduce HVAC energy use in high-rise multifamily buildings in each of the three California Climate Zones modeled.

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