

Design and Optimization of a Mixed Mode Raised Floor and Natural Ventilation System for a High Rise Office Building

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ABSTRACT

This paper describes the design and analysis of a mixed mode ventilation system for a high rise office building. The proposed building site is situated in downtown San Francisco, an ideal climate for a mixed mode system. The innovative system design utilizes a raised floor for under-floor air distribution in conjunction with automatically controlled operable openings in the building's facade to heat, cool, and ventilate the occupied space. Bulk airflow study and thermal analysis modeling were used to develop the system concept, maximize the number of effective natural ventilation hours, determine energy saving control schemes, and demonstrate the mixed mode system would maintain the indoor design criteria. Energy analysis and lessons learned are included to provide cost and performance suggestions to contribute to existing design best practice.

Introduction and Background

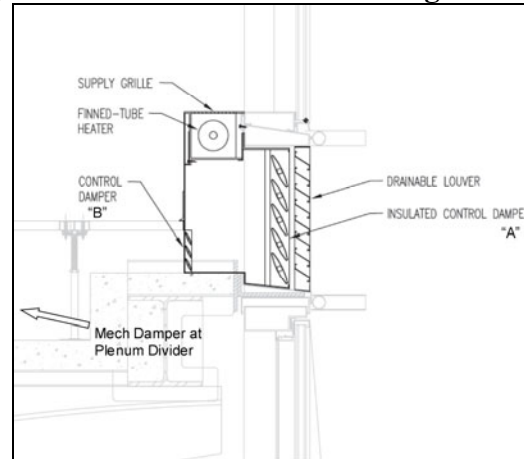
Mixed mode ventilation refers to strategies that incorporate both natural and mechanical ventilation on an individual space or whole building scale. The Center for the Built Environment (CBE) at the University of California Berkeley provides a broad definition of mixed-mode systems, separating them into two broad categories: zoned and complimentary. The building incorporates a “zoned” mixed mode strategy because core building zones will always be served by a mechanical system, while the perimeter is “complimentary” as it may be served by natural or mechanical means. The uniqueness of this particular design concerns its ability to “changeover” (a CBE subcategory) between natural and mechanical modes. Though “concurrent” strategies, those that use mechanical and natural ventilation simultaneously, do not necessarily waste energy, they do not take full advantage of energy savings that could be achieved by isolating the two modes when possible. In San Francisco, where the mild weather allows mechanical systems to use air-side economizers to reduce or eliminate cooling energy for much of the year, the most substantial energy savings associated with mixed mode are connected to fan energy. For this reason, the design team pursued a strategy that would allow all mechanical ventilation to cease at the perimeter when natural ventilation became available.

System Description

The system design includes a raised floor supply air with manual and automated operable façade openings. These openings include automated “trickle vents” at the low level, manually operated windows at vision level, and top-hung automated windows near the ceiling. The trickle vent is an assembly of louvers, control dampers, and a hydronic finned-tube heater that replaces spandrel within the curtain wall. Unlike typical trickle vent assemblies, the vent is situated adjacent to the raised floor plenum, supplying outdoor ventilation air to the supply plenum rather than directly to the occupied space. In order to promote automated “changeover” system control,

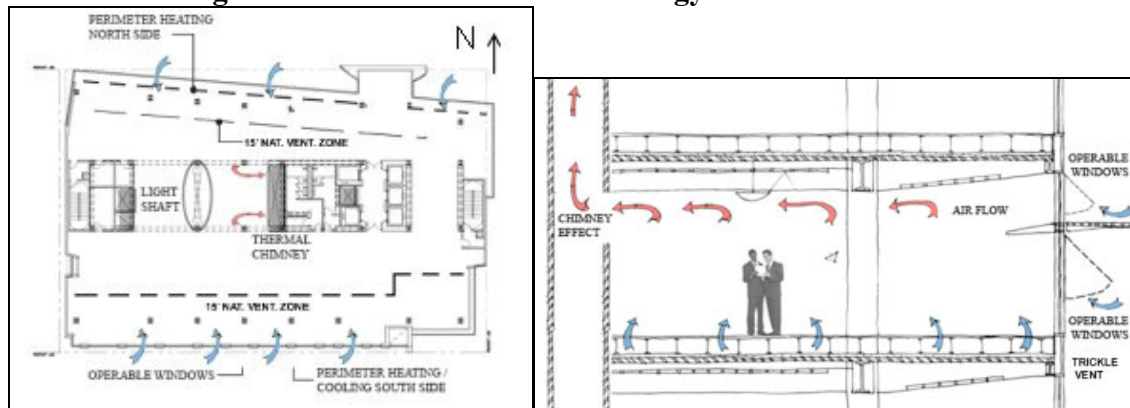
the design requires a custom automated trickle vent assembly, illustrated below, that can allow outside air to pass through the façade or close to allow the mechanical system to pressurize the perimeter plenum.

Figure 1. Trickle Vent Section Diagram



There are three “thermal chimneys” running vertically through the core of the building that relieve pressure created by wind-driven airflow. These chimneys also create a stack effect that can help to induce natural airflow when there is little or no wind to drive air through the building. The north and portions of the east and west facades will have trickle vents only, whereas the south and remaining sections of the east and west facades will have low level trickle vents and high level operable windows. Figure 2 shows a typical plan view showing naturally ventilated zones and a building section illustrating perimeter zone airflow in natural ventilation mode.

Figure 2. Natural Ventilation Strategy Schematics



The mechanical system includes a water-cooled chiller plant and a hot water boiler with a central rooftop air-handling unit that pressurizes the underfloor plenum during all occupied hours. The plenum includes sheet metal dividers with motorized dampers to isolate the perimeter zones (within 15’ of the façade) from the interior, which is always mechanically ventilated. The motorized dampers, facade openings, heating elements, and central fan are

sequenced and controlled together to provide maximum energy savings throughout the year, as discussed in the “controls” section of the report.

Engineering Challenges

Since the building is a high rise, mixed mode ventilation presents more design challenges than for typical low-rise buildings. In addition to thermal and ventilation design criteria, the system must manage fire and smoke to protect life safety. All the openings can be automatically closed by the building management system (BMS) in case of fire; however, local code officials are not prone to trust that so many actuators will consistently operate effectively over time. Therefore separate studies are being performed to demonstrate that the building can maintain the necessary level of safety required for egress of the building in an emergency.

Complimentary mixed mode strategies by definition provide system redundancy, which necessarily multiplies system cost. Each perimeter space has the ability to be heated, ventilated, or cooled by either a mechanical option or a passive option. As a result, fans and sheet metal distribution components must be purchased as well as operable windows and actuators. In addition, the innovative “changeover” functionality afforded by this design requires the development of a custom trickle vent module that can be integrated neatly within the architectural curtain wall system. The design team coordinated with manufacturers to simplify the trickle vent, but its custom nature adds cost to production and thus to the final project cost.

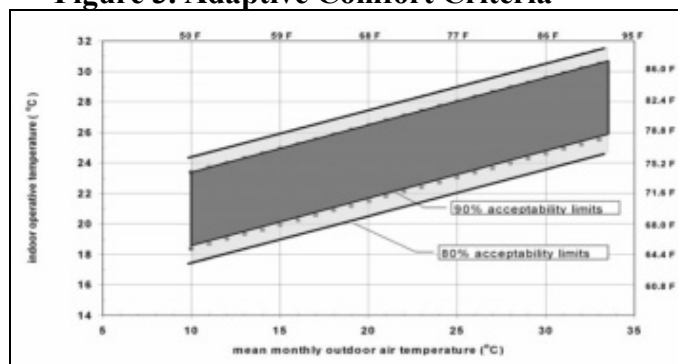
Finally, best practice simulation methods and tools for mixed mode ventilation have not been clearly established. The design process included full-building bulk airflow analysis to determine ventilation rates in the building under a variety of conditions. Calculated airflow rates were used in a separate thermal analysis tool to determine whether natural ventilation can provide comfort and maintain the design criteria in each perimeter zone. Integrated analysis tools are available in the marketplace, but a survey of available products revealed limitations in one or more of these analysis stages. One purpose of this study was to outline the requirements for an efficient analysis and design methodology for the layout and control of mixed mode systems.

Analyses

Design Criteria

ASHRAE Standard 55-2004 establishes the thermal comfort criteria and ASHRAE Standard 62.1-2007 establishes the ventilation requirements that guide the system design, modeling methodology, and control sequence development. For environments where occupants can control their thermal comfort by opening a window, ASHRAE Standard 55-2004 offers an alternate comfort range known as the “adaptive comfort” criteria, illustrated in Figure 3.

Figure 3. Adaptive Comfort Criteria



In San Francisco, September, the warmest month, has a mean monthly outdoor air temperature of 62°F (16.7°C), which suggests that the acceptable operable temperature range for the summer indoor design condition is between 67°F and 80°F. In December and January, the mean monthly temperature falls slightly below 50°F (10°C), but for all other heating months the adaptive comfort criteria suggest indoor design conditions between 62°F and 75°F when operable windows are accessible. Because the adaptive comfort range spans 13°F, there is some subjectivity in selecting effective indoor design criteria for thermal comfort. The analyses in this report use different indoor drybulb temperature setpoints in reference to the adaptive comfort range as shown in the table below.

Table 1. Modeling Design Criteria

Simulation	Summer Indoor Setpoint	Winter Indoor Setpoint	Ambient Temperature
Bulk Airflow (VENT)	75°F	not analyzed	60°F, 65°F, 70°F
Energy (eQuest)	78°F	70°F	Hourly data

The indoor design criteria are especially important for the energy model as they determine the changeover criteria between natural and mechanical ventilation at the threshold of uncomfortably warm or cold conditions. The bulk airflow analysis uses 75°F as the internal temperature to provide conservative buoyancy-driven airflow results. The higher the assumed indoor air temperature, the more buoyancy will drive natural ventilation airflow.

ASHRAE Standard 62.1-2004 establishes outdoor air ventilation requirements based upon floor area, number of occupants, and type of occupancy. In an effort to promote the highest indoor air quality, this project is designed to exceed the requirements of ASHRAE 62.1-2004 by 30%, per the LEEDTM performance credit for improved ventilation. The building is designed to provide at least 22.1cfm per person of outside air. If this quantity of air cannot be provided by natural ventilation at any time, the mechanical system must be activated.

Bulk Airflow Analysis

Early in the development of the design, ventilation calculations were performed using the Oasys VENT software tool to estimate the amount of air entering the space based on different wind speeds. VENT uses building geometry and facade opening properties to determine airflow through each space in the building under a single set of internal and external conditions. It is classified as a bulk airflow tool because VENT only calculates air inflow and outflow, treating the actual space as a single node. The required opening properties include dimensions, discharge

coefficient (C_d), discharge exponent (n), and pressure coefficient (C_p). The following relationships exist between these parameters, wind speed (U), air density (ρ), and airflow through an opening:

$$\text{Airflow} = C_d \cdot D \cdot \Delta p^n$$

$$\Delta p = C_p \cdot \frac{1}{2} \cdot \rho \cdot U^2$$

The following table shows the pressure coefficient assumptions made in the analysis, based upon Chartered Institution of Building Services Engineers (CIBSE) empirical data for buildings with 2:1 aspect ratio and surrounding obstructions equal to half the height of the building. The predominant wind direction is WNW at the site, so the pressure coefficients were selected based upon westerly winds. Because the north facade is angled slightly toward the east, its pressure coefficient is slightly less negative than the south facade, which faces due south.

Table 2. Pressure Coefficients

Opening Direction	Pressure Coefficient
East	-0.3
North	-0.3
South	-0.35
West	0.4
Horizontal Roof	-0.8

The discharge coefficient is assumed to be 0.83 and the discharge exponent 0.5 for all external openings, accounting for the dynamic losses associated with air moving through a one-directional flow orifice. High level top-hung windows are assumed to open at an angle greater than 30° so that the window area in the facade plane is smaller and more restrictive than the actual window open area. Based upon this assumption, the analysis considers hung windows to have the same discharge coefficient as a standard hinged window. Internal openings are modeled as 10 discrete one-way orifices with discharge coefficient of 0.553 and discharge exponent of 0.5. VENT solves a large system of the nonlinear airflow equations (one equation for each orifice plus boundary condition equations) to resolve all building flows. A 3-D rendering of the model used is shown in Figure 4 below along with a pair of schematic flow diagrams in Figure 5. The flow schematics reflect the model geometry shown in Figure 4. Though the thermal chimneys are in the building core, the model was simplified and not affected by ignoring the portion of the core space east and west of the thermal chimneys.

Figure 4. Ventilation Model

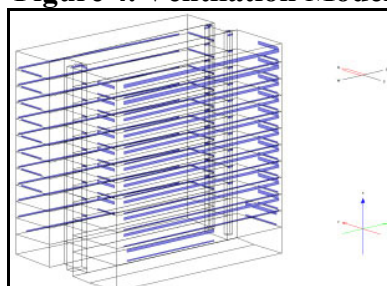
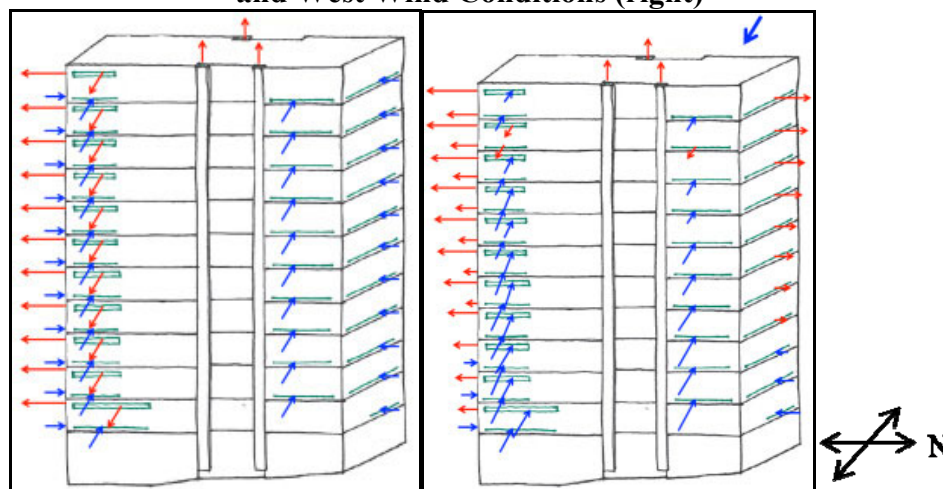


Figure 5. Isometric Airflow Schematic, Still Conditions (left) and West Wind Conditions (right)



Initially the VENT tool was used to quantify the airflow benefit of increasing size and the separation distance between low and high level openings. Once the design team agreed upon optimized and feasible opening geometry and configuration, the analysis was run under a variety of conditions to develop a functional relationship between ambient temperature, wind speed, and the resulting airflow. The analysis was conducted at 60°F, 65°F, and 70°F ambient temperature with each of 0, 8, and 15 miles per hour westerly wind conditions while holding internal conditions constant per the design criteria. The nine test conditions were used to generate a family of curves that can be used to predict airflow under different temperature and wind conditions that were used in thermal analysis.

The results indicate that for all studied wind conditions approximately 5% of natural ventilation air exits the building through these relief shafts. Since thermal chimney flow is “pinned” at maximum under all wind conditions and chimney area is small relative to façade opening area, the results imply that enlarging relief stacks would increase building airflow, especially under low wind conditions.

Thermal Analysis

After available airflow was determined through bulk airflow analysis, thermal load was estimated by summing anticipated coincident loads at the building cooling peak. Required supply airflow to maintain space temperature was calculated by applying the following equation for sensible heat flow through air at standard temperature and pressure conditions.

$$Airflow_{cfm} = CoolingLoad_{Btu/hr} \div (1.08 \cdot (T_{indoor} - T_{ambient}))$$

This calculation ignores latent heat gain and operative temperature, which should generally be considered when anticipating thermal comfort. However, since San Francisco air is consistently dry and surface temperatures are assumed to be close to the indoor air temperature, only sensible heat transfer was considered for simplicity.

The following table lists the load assumptions that were used in the thermal analysis. Since the space conditioning strategy allows heat to stratify, a portion of each load is assigned

directly to the return plenum. The building will include automated shades, which CBE research found in one perimeter zone empirical study to communicate 48% of solar radiation load directly to the plenum (Webster 5). Also per CBE recommendations, the analysis assumes that 30% of the stratified load from the floor below is transmitted through the floor slab into the supply plenum above (HPAC Engineering, July 2006).

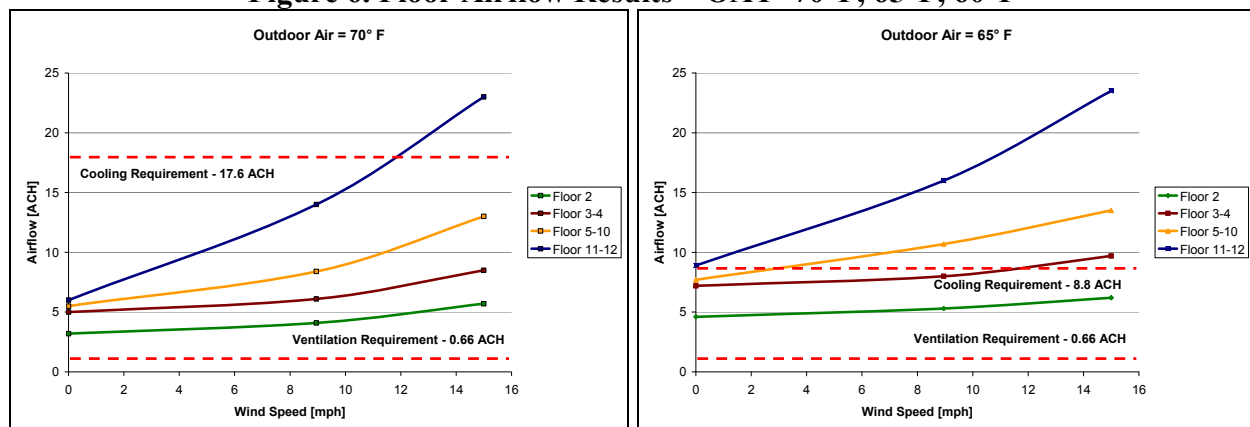
Table 3. Load Assumptions

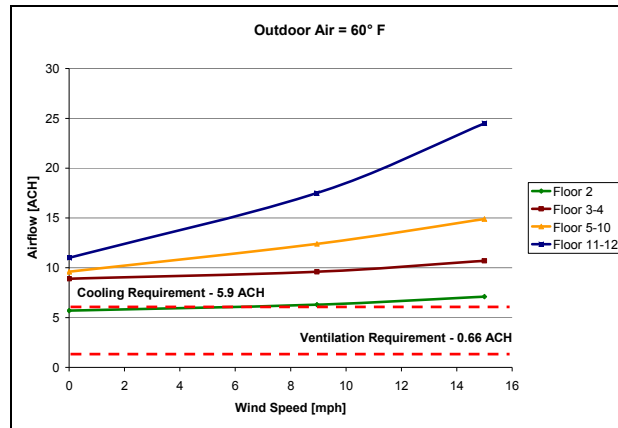
	South		North	
Perimeter Area per Floor	2,312 ft ²		2,218 ft ²	
	Load	Load to Plenum	Load	Load to Plenum
Lighting	0.8 W/ft ²	50%	0.8 W/ft ²	50%
Equipment	1.35 W/ft ²	33%	1.35 W/ft ²	33%
People	150 ft ² /person	0%	150 ft ² /person	0%
Solar	215 Btuh/glass ft ²	48% (internal shade)	54 Btuh/glass ft ²	48% (internal shade)
Slab Conduction	30% of plenum gain		30% of plenum gain	
Total Load	28 Btuh/ft ²		14 Btuh/ft ²	
Total Required CFM	4,000 (60°F) – 6,000 (65°F) CFM		2,000 (60°F) – 3,000 (65°F) CFM	

The bulk airflow results are illustrated in the following charts in terms of air change rate per hour (ACH) with the required airflow for cooling and ventilation shown as a red dashed line. The flow rate should vary as the square root of the sum of the squares of the wind and thermal buoyancy pressures. Figure 6 illustrates the aggregate airflow behavior by floor. Theoretically, at high wind speeds the airflow should increase linearly with wind speed as the contribution of buoyancy diminishes.

The required airflow to meet the cooling load increases as the outdoor temperature increases. Because buoyancy pressure falls as outdoor air temperature rises closer to that of indoor air temperature, the available airflow decreases as outdoor temperature increases, precisely when more airflow is needed. Available airflow converges at higher wind speeds as wind pressure becomes the dominant airflow driver and the contribution of buoyancy diminishes.

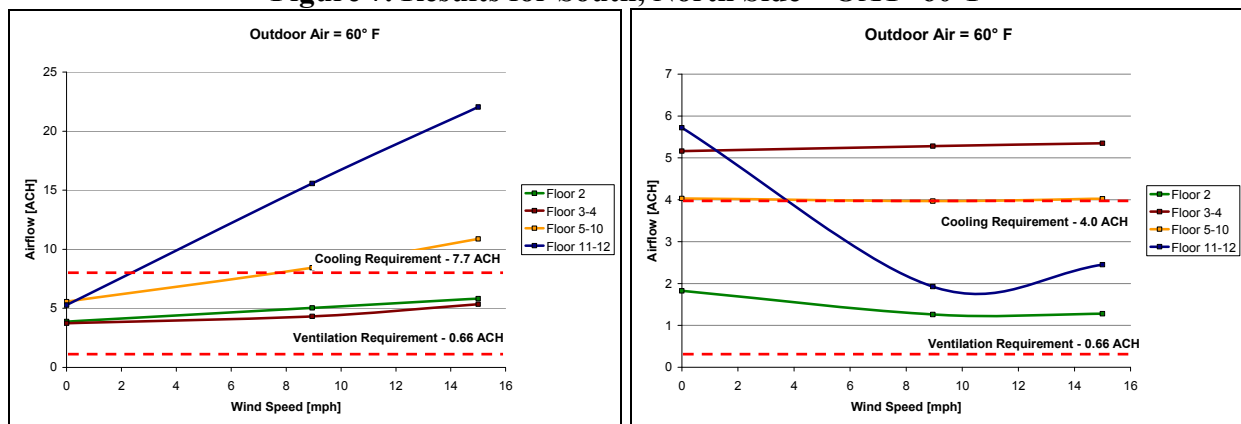
Figure 6. Floor Airflow Results – OAT=70°F, 65°F, 60°F





Natural ventilation airflow and load are separated into north and south perimeter zones in Figure 7 to illustrate that supply airflow and load cannot simply be averaged across an entire floor plate. Because opening size, number, location, and wind pressure coefficients vary between the north and south exposures, available airflow through the north and south perimeter facades differs as wind speed changes. Airflow on the south facade corresponds roughly to that of the building as a whole, increasing as wind speed increases. The north facade, however, exhibits a complex response to increasing wind speed. Lower speed winds oppose buoyancy flow at low and high floors, causing overall airflow into openings to fall. As wind speed continues to increase, however, the airflow behavior changes modes and begins to increase once again as wind pressure increases. Mid-level floors near the neutral plane of the building exhibit fairly constant airflow under all wind conditions on the north facade. Further research should be done to fully explain the complex airflow interactions among spaces and floors in an asymmetric building.

Figure 7. Results for South, North Side – OAT=60°F



Energy Analysis

The thermal analysis reveals to what extent natural ventilation can or cannot meet the cooling and ventilation load at each perimeter zone under design conditions. It does not clarify how many hours per year the natural ventilation mode will operate within each zone, and thus, the thermal study can make no claim about annual energy savings. Since understanding energy

performance is important for financial analysis and justifying client investment, an eQuest building simulation model was developed to quantify energy savings associated with the mechanical underfloor air system versus a baseline system and the savings linked to the mixed mode strategy. The baseline model was built following ASHRAE Standard 90.1-2004 Appendix G methodology. The baseline features a variable air volume system with variable speed fans, standard efficiency motors, an atmospheric hot water boiler plant, and a centrifugal chiller for cooling with the minimum efficiency levels recommended by ASHRAE 90.1-2004.

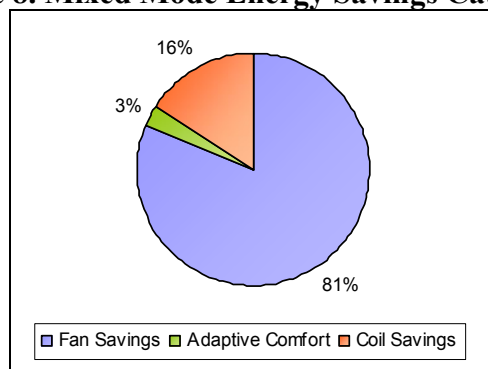
The eQuest model indicates that the underfloor air system without mixed mode saves 11.3% overall energy versus the baseline building. These savings can be attributed to additional economizer hours from elevated supply air temperature, less supply system static pressure, and cooling load stratification. In order to determine energy savings attributed to the mixed mode strategy, eQuest does not accept external input regarding anticipated airflow under different ambient temperature and wind speed conditions. As a result, the VENT analysis and thermal study results were not considered by the eQuest model. Instead, eQuest uses the Sherman-Grimsrud equation along with default parameters to estimate wind and stack pressures from wind speed and inside-outside temperature difference.

eQuest uses the resulting airflow from the Sherman-Grimsrud algorithm to determine whether the space temperature can be maintained without the use of the mechanical system. If the load can be met by outdoor air, eQuest isolates the perimeter zone from the mechanical system provided three additional criteria are satisfied. First, mixed mode availability must be confirmed by referring to an hourly on/off schedule. Second, the resulting indoor temperature when windows are opened must keep the space temperature above the upper end of the heating setpoint throttling range in order to avoid triggering the heating system. Finally, eQuest applies a fractional probability hourly schedule to determine the chances that a particular opening will be activated when conditions are appropriate. This building has constant availability and 100% opening probability because windows and vents are actuated by the BMS. Based upon the eQuest calculation, mixed mode provides an additional 1.1% overall energy savings beyond the 11.3% UFAD energy savings, or \$5,600 per year. The perimeter south-facing zone with low and high-level openings on floor 11 replaced mechanical ventilation and cooling with natural ventilation for 17% of active system hours. The north-facing zone on floor 11 entered natural ventilation mode for 9% of active system hours. The number of natural ventilation hours is unrealistically low, which is likely the result of eQuest calculating that the space would be overcooled by natural ventilation if the mechanical system were shut off.

The second mixed mode “changeover” criterion listed above explains why eQuest, which cannot model a perimeter fin tube heater inline with trickle ventilation, underestimates mixed mode energy savings. Whenever the outdoor air temperature falls much below the high end of the heating throttling range (70°F), eQuest closes the windows as the indoor air condition approaches that of the outdoors. To more accurately account for the true natural ventilation mode operational hours in swing and heating seasons, an additional energy savings study was conducted. The spreadsheet-based calculation uses the airflow relationships calculated using VENT to conduct sensible heat balance calculations at every hour of the year based upon ambient temperature and wind speed from local weather data. As expected, the manual calculation, which accounts for winter fan savings, indicates larger mixed mode energy savings of \$15,980 per year, or 3.0% of whole building use. The total building energy savings from combining the raised floor and mixed mode operation using the spreadsheet result is 13.5%, or \$64,412. The spreadsheet calculation also generates interesting data that explains the source of

these energy savings as shown in the figure below. “Adaptive Comfort” refers to the fan energy benefit associated with more natural ventilation mode hours made possible by increasing the acceptable dry-bulb air temperature range by 3°F. Coil savings refers to chiller or boiler savings associated with mechanical system use when the airside economizer alone cannot provide appropriate air temperature.

Figure 8. Mixed Mode Energy Savings Categories



The fan savings dominate the mixed mode benefit because the San Francisco climate makes the airside economizer very effective, limiting the usage of chilled water during cooling months. Since the fans generate almost all energy savings, the analysis confirms that it is indeed worthwhile pursuing a “changeover” type mixed mode system in the San Francisco climate to minimize fan use. Climates that have more humidity and extreme heat may achieve a larger percentage of savings at the cooling and heating coil, and concurrent mixed mode systems may offer much simpler yet effective solutions.

Control Strategies

Though further analysis will be required to refine actual window opening sequences and stages, the general control strategy for the mixed mode system has been determined and is outlined in this section. The Federal Building in San Francisco used EnergyPlus and CFD to develop a 10-stage natural ventilation control sequence based upon external wind and temperature to achieve maximum energy savings and comfort. This project plans to use simpler controls based upon the same principles. The following table illustrates the basic mixed mode control strategy without considering varying wind speed and the specific number of openings active within each stage. The dampers referenced in the table and controls discussion are labeled in Figure 1.

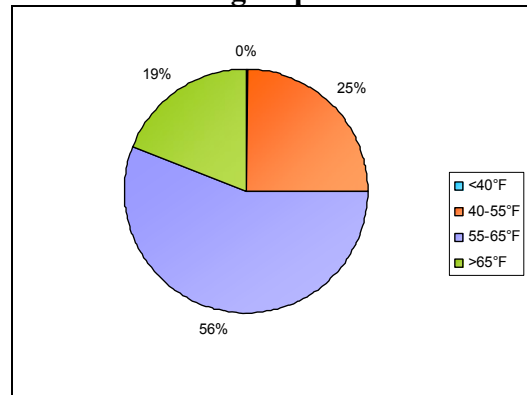
Table 4. Mixed Mode Control Sequence Outline

Approximate Ambient Temperature Range	Damper A Position	Damper B Position	Mechanical Supply Damper	High-Level Window Position	Heating Element Status
<40°F	closed	open	minimum	closed	on
40°F-55°F	minimum	closed	closed	closed	on
55°F-65°F	open	closed	closed	open	off
>65°F	closed	open	open	open	off

Based upon the VENT and thermal analysis results, each exposure and floor will have different ambient temperature thresholds for the natural ventilation mode. All control temperature ranges will be adjusted and refined in later stages of analysis and during building occupancy as needed. Exposures and floors will be grouped together as necessary to simplify the control strategy.

The preliminary control sequence outline provides a framework for analyzing how often each control stage will be used during a typical year. TMY3 weather data for San Francisco indicates that the ambient temperature aligns with the temperatures associated with each control stage as shown in the Figure 9 following.

Figure 9. Control Stage Operational Distribution



The figure indicates that mechanical cooling and ventilation will potentially only be needed in mixed mode perimeter zones (~20% of conditioned floor area) for 19% of operational hours, leading to estimated 28% building fan energy savings versus standard UFAD. The outdoor temperature is almost never below the minimum threshold, and both trickle vents and high-level windows will be utilized for 56% of occupied hours. This early analysis of specific control schemes provides further encouragement that the San Francisco climate produces attractive fan energy savings because so many hours can be served by the natural ventilation mode.

Lessons Learned

The energy savings from the mixed mode system are primarily related to fan energy, which illustrates the benefit of changeover mixed mode systems in mild climates that can completely isolate mechanical fans. Though higher energy savings are achievable with changeover systems, they add a considerable amount of complexity as dampers and plenum dividers must be included to isolate the perimeter zone. This project required custom analysis methodology and trickle vent assembly to achieve additional fan energy savings. As mixed mode design tools and facade products develop further, both the cost and effort associated with implementing a changeover system should diminish. However, because mixed mode systems require that two redundant ventilation systems be installed, their life cycle cost will tend to not pay back based upon energy cost savings alone. Other intangible factors such as improved indoor air quality, occupant satisfaction, and worker health and productivity must also be considered in making a decision to employ complimentary mixed mode systems.

Aggressive system design and more lenient occupant comfort criteria could make mixed mode systems much more cost effective. Central systems and distribution can be downsized if some spaces, typically north-facing, can be completely naturally ventilated. Ceiling fans and exposed thermal mass can help promote occupant comfort when mechanical systems are eliminated. If the challenge of changeover or completely naturally ventilated design cannot be achieved, concurrent mixed mode systems, though they will not reduce fan energy, can save some cooling energy as natural ventilation can meet a portion of the load. If underfloor fan terminals are employed for heating and peak cooling conditions at the perimeter, a simple contact on the window can be used to isolate the fan motor and heating hot water control valve. By isolating the terminal fan and heater, the perimeter zone is guaranteed minimum ventilation air through the underfloor plenum while minimizing zone energy consumption when windows are open. These more conventional approaches, though arguably less energy efficient in climates like San Francisco, have been implemented successfully, can be relatively simple to design, and offer low risk of occupant discomfort.

Changeover strategies are an exciting application of mixed mode systems, and this project reveals the opportunities and challenges of implementing innovative mixed mode strategies in an urban high rise building. The bulk airflow, thermal, and energy analyses together provide a good description of system performance, potential energy savings, effective control sequences, and the occupant experience in individual spaces. Hopefully the project will inspire others to implement changeover mixed mode and contribute further toward the development of design best practice.

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