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Overview of Hybrid Ventilation Control System and Full Scale Monitoring

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ABSTRACT

Mix-mode or hybrid ventilation systems have been previously shown to reduce cooling and ventilation energy consumption. This paper presents a case study of a new ten story 83,700 ft² (7,780 m²) office building in downtown Tokyo with a hybrid ventilation system that uses only 1.7% of the building footprint for ventilation shafts. The control system design is presented as an example of balancing the comfort expectations of multiple tenants in a mix-mode system. On-site measurements are presented from a three week commissioning project to show: modest temperature differences within the occupied zone with a maximum difference of 1.5 °F (0.83 °C), large differences of up to 6.1 °F (3.4 °C) between the measured outdoor temperature in the control system and the actual inlet temperature for the natural ventilation system, the importance of smooth integration of various design teams, and the use of low-power fans, 1.2-0.60 hp (900-450 W), that leverage the low pressure drop through the building when natural driving forces are insufficient for pure natural ventilation. Practical lessons learned from the design and commissioning of the building are also shared.

INTRODUCTION

Hybrid ventilation systems, consisting of natural and mechanical ventilation, offer potentially significant energy savings through the use of natural ventilation (NV) with suitable outdoor conditions, while maintaining indoor comfort conditions with mechanical ventilation with chillers when natural ventilation cannot be used. A major challenge in the design and operation of a building with hybrid ventilation is the control system. Not only do the controls need to regulate natural ventilation flow rates, which highly depend on dynamic parameters, but they also need to intelligently switch between the natural and mechanical ventilation systems. Tenant buildings with hybrid ventilation introduce another challenge of maintaining different comfort standards throughout various zones within the building.

This paper presents a case study of the control system of a hybrid ventilation tenant building in downtown Tokyo. The building is briefly described, then the control system is outlined, on-site measurements are presented to evaluate the control system, and lessons learned are shared.

BUILDING DESCRIPTION

The ten story 83,700 ft² (7,780 m²) office building uses only mechanical ventilation on floors 1, 3, and 10 and hybrid ventilation on all other floors. Figure 1 shows an external photograph, plan view, and photograph of the open-plan interior.

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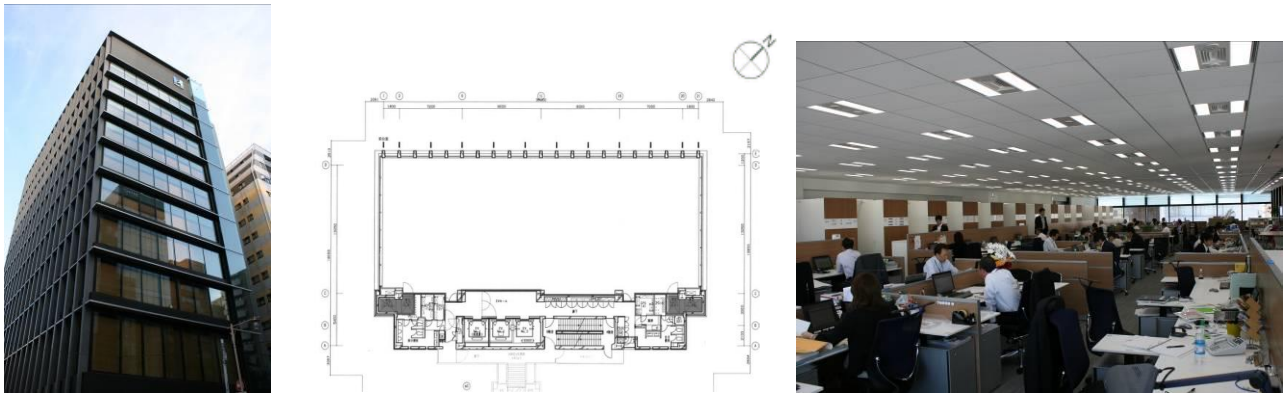

Figure 1 *(left) Outer view from west (middle) plan view with ventilation shafts shaded (right) open-plan interior.*

Inlets on the NW façade supply outdoor air to floors 2 and 4-9 when the natural ventilation system is in operation. An open floor plan allows air to flow to two ventilation shafts located in the SE side of the building, which occupy less than 1.7% of the building floorplate. To prevent reverse flow in the upper floors, two shafts, each with 30 ft² (2.8 m²) cross sectional area are used to ventilate floors 2 and 4-7, and two other shafts (22 ft² (2.0 m²) each) are used to ventilate floors 8 and 9. Figure 2 shows a schematic of this separation including binary dampers at the facade inlets and adjustable dampers at the entrances to the ventilation shafts.

Low-power fans (1.2 hp (900 W) and 0.60 hp (450 W) for shafts 2-7 and 8-9 respectively) mounted just above the tenth floor atop each ventilation shaft leverage the low airflow resistance of the building to extend the period during which fan-assisted natural ventilation can be used.

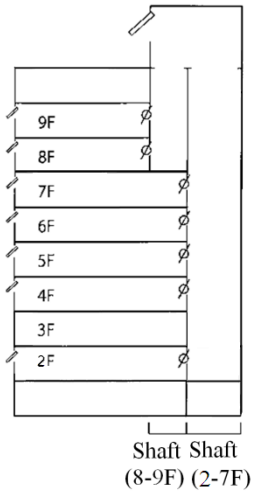

Figure 2 *Schematic of ventilation path showing separate shafts for floors 2-7 and 8-9.*

HYBRID VENTILATION CONTROL ALGORITHM

To accommodate different comfort expectations within the tenant building, four operational modes have been established by the building owner. Mode A provides pure natural ventilation as long as ambient conditions allow for acceptable indoor conditions, which will be defined later. If ambient conditions allow, the system is reset, turning off all fans and opening all openings, at 12:00, 18:00, and 22:00 in case occupants have manually shut openings, but have not re-opened them after ambient conditions have changed. Mode B prioritizes natural ventilation, but allows users to turn on any of the eighteen fans on each floor within the mechanical direct-expansion units whenever they like to create additional air movement in the space. No compressors can be used when NV is in use, only the fans. However, as in Mode A, the system is reset three times a day. Mode C uses natural ventilation, but prioritizes occupant comfort by allowing the use of the direct-expansion unit fans at any time with no reset. Mode D provides strictly mechanical cooling and ventilation. Users can manually close the natural ventilation inlets in all modes; if all inlets are closed, the mechanical system turns on.

Figure 3 illustrates the core structure of the natural ventilation control algorithm. The building has been designed with the potential future use as a tenant building, in which case individual floors may be divided into two zones. For this reason, each floor is divided into two independently controlled zones. However, given that no floor is physically divided into separate zones by the current occupants, the two control zones on each floor are essentially operated in unison.

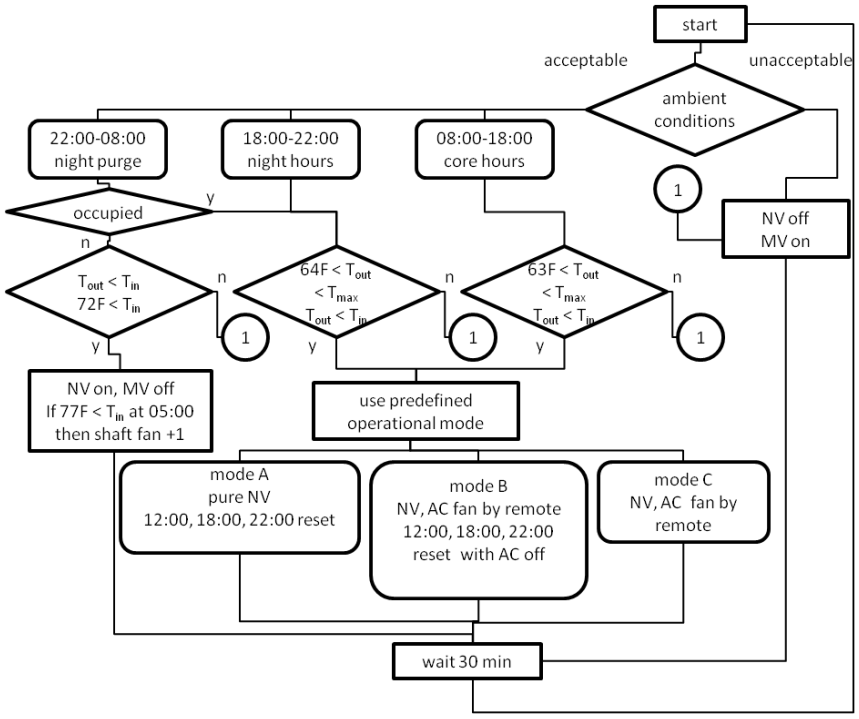

Figure 3 *Core structure of NV control algorithm highlighting various operational modes.*

set point in Japan.

Thermal mass within the building is pre-cooled over night using night purge, which leaves natural ventilation openings open over night to allow cool night air to flow through the building. If insufficient air flow through the building occurs over night and the indoor temperature is greater than 77°F (25 °C) at 05:00 and $T_{out} < T_{in}$, low-power auxiliary fans turn on to force outdoor air through the building. These fans can also be used during the day if natural ventilation is deemed acceptable based on ambient conditions, but natural driving forces are not strong enough to provide sufficient airflow to meet indoor comfort conditions. Between 08:00 and 22:00, these fans will turn on if the indoor temperature in two or more floors is within 4 °F (2 °C) of T_{max}, as shown in Figure 4. The other floors will experience a higher flow rate when the fan turns on, but are maintained at an acceptable indoor temperature by the automatically adjusting dampers to the ventilation shaft. If the air temperature in two or more floors is still within 4 °F (2 °C) of T_{max} after ten minutes, the fan speed is increased by one of three steps to force more air through the building. If after ten minutes the air temperature in all floors is at least 4 °F (2 °C) below T_{max}, the fan speed is decreased by one step.

Natural ventilation is deemed acceptable when the ambient conditions meet the following requirements: RH < 80%, wind velocity < 34 mph (15 m/s) for previous 15 minutes, precipitation < 0.08 inches (2 mm/hr), 64 °F (18 °C)< T_{out} < 79 °F (26 °C). A second restriction on allowable ambient temperatures is applied based on time of day, which closely correlates with occupancy. All ambient weather conditions are measured with a rooftop weather station. Whenever natural ventilation is used, the adjustable dampers to the shaft are adjusted every minute to regulate airflow based on indoor temperature as shown in Figure 4. The maximum temperature T_{max} in Figures 3 and 4 changes throughout the year between 77 – 82 °F (25 – 28 °C) based on the adaptive comfort model in ASHRAE 55 (ASHRAE 2011). The 82 °F (28 °C) max in Figure 4 is used during the summer and is the nationwide recommended summertime

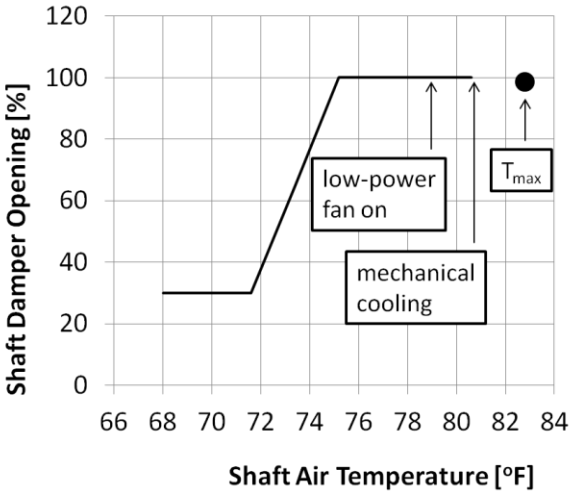

Figure 4 *Temperature-based control of dampers to ventilation shaft. The low-power fan and mechanical cooling turn on relative to T_{max}, which changes with seasons.*

MEASURED BUILDING PERFORMANCE

Over 2300 permanently installed sensors monitor the building performance at various frequencies – two minute, ten minute, and hourly. Numerous parameters are measured including temperatures, humidity levels, opening positions, light/plug/misc electricity usage per half floor, air velocities, weather data, and system properties. Along with these ongoing measurements, additional measurements made throughout the year will provide even more building performance information. Intensive three-week measurements were made between October 8-25, 2012 to provide volumetric airflow rates, higher resolution temperature distributions, and airflow visualization. Although the airflow visualization videos are not presented in the paper, they will be presented at the conference.

Horizontal Temperature Distribution

The NV inlet openings in each zone are controlled by a single temperature measurement taken from the back of the space. Ideally, the indoor temperature would consist of some kind of average temperature for the zone, or from a representative area within the zone – near occupants – if only one measurement were made. Flexible use of each floor and the potential for new tenants required the measurement to be taken from the back wall. To investigate the difference between this measured temperature used in the control algorithm and the temperature of the occupied area within each zone, the horizontal temperature distribution was taken on floors 6-9 using numerous wireless temperature sensors placed throughout the occupied space at desk height. A ten minute sampling rate was used with the sensors that have a stated accuracy of 1 °F (0.5 °C). Special care was taken to ensure direct heat sources, such as lamps or computer exhaust air, did not artificially skew the measurements. Figure 5 shows the average difference between each wireless sensor, indicated by a circle, and the wall-mounted permanent sensor used in the control algorithm, indicated by a star, measured during October 8-24 on the sixth floor. Temperatures measured while the mechanical ventilation and cooling and natural ventilation systems were in use have been averaged in the MV and NV bins respectively.

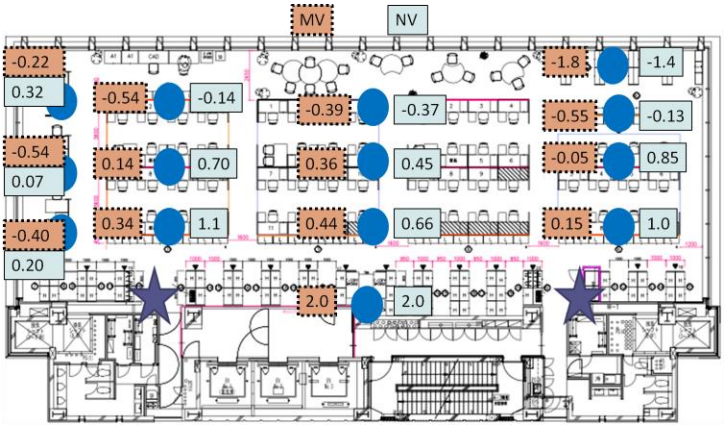

Figure 5 *Average temperature differences in °F between wireless sensors, circles, and wall-mounted sensors used in control system, stars, on the sixth floor measured between October 8-24, 2012. MV and NV indicate temperatures measured during mechanical and natural ventilation*

Excluding the sensors on the far left, which were placed under three rarely used desks and removed from the NV airflow, all the NV temperatures nearest the inlet façade were below the control system temperature measured at the back wall, indicated by a star, as expected. The incoming outdoor air was coldest when it entered the building before it was heated by internal heat gains. The NV temperatures rose as they approached the back wall to about 1 °F (0.5 °C) above the measured wall temperature. These temperatures were higher than the control system temperature because they were taken in the middle of the most intense heat sources in the space – occupants working on their computers. The control system temperature measured the air temperature after much of the air in the space had mixed, which distributed the more intense heat gains to air that flowed through aisles and less densely populated desks. Temperatures in the middle of Figure 5 reveal lower NV temperatures taken at the end of a row of desks that bordered an aisle than the temperatures measured in the middle of a row of desks. These aisle-bordering temperature differences ranged from -0.37 to 0.66 °F (-0.20 – 0.37 °C), while the temperature differences taken in the middle of a row of desks were generally higher those taken along the aisle due to increased heat gains and ranged from -0.14 to 1.1 °F (-0.08 – 0.61 °C). The largest difference between NV temperatures and the control system temperature was 2.0 °F (1.1 °C) taken from the copy room located along the back wall in the middle of

the floor. Very little airflow occurred in the room, which had large plug loads. The largest range between NV temperature differences was 3.4 °F (1.9 °C); the copy room was 2.0 °F (1.1 °C) above and the temperature nearest the inlet façade was 1.4 °F (0.78 °C) below the control system temperature. However, within the occupied zone of the desks, the largest range was 1.5 °F (0.83 °C).

The MV temperature differences show a smaller range of temperatures within the occupied zone of the desks with a largest range of 0.98 °F (0.54 °C). However, an even larger range of temperature differences was observed between the copy room and the point located along the inlet façade, 3.8 °F (2.1 °C). Another area of interest was the row of desks located along the left-most façade, which were very sparsely occupied. The MV system routinely over cooled this area that had very few heat gains.

Measuring Ambient Air Temperature

The use of NV highly depends on outdoor air temperature and humidity of the incoming air, so an accurate measurement of these ambient conditions is essential for the control system. However, for this and many buildings, ambient weather conditions are measured by a roof-top weather station mounted away from all mechanical equipment on the roof that would otherwise artificially impact the measurements. Although the weather station accurately measures the temperature and humidity on the roof, the air temperature of the incoming air through the NV system can be significantly different. Figure 6 plots the measured ambient temperature from the roof-top weather station, T_{roof}, the temperature of incoming air measured in the NV façade inlet, T_{inlet}, and the NV system status, NV on/off, over the course of four October days. After NV turns on, T_{inlet} rapidly drops because of the transition from MV to NV. Since these measurements do not accurately measure the incoming air temperature, they should not be used to compare T_{inlet} to T_{roof}. Two major effects can cause T_{roof} to differ from T_{inlet}. First, the roof is directly exposed to the sun, while the inlet façade on the northwest side of the building is never exposed to direct sunlight. Even though the temperature sensor in the roof-top weather station is shielded from direct radiation from the sun as shown in Figure 7, the measured temperature on the roof can be much higher than the inlet temperature on a sunny day. During the sunny day of October 22, T_{roof} was up to 5.4 °F (3.0 °C) higher than the measured inlet temperature. This difference would likely be increased during the summer when the sun is closer to the earth. The second major effect is direct exposure of the roof to the cold night sky. The roof has a very large view factor to the sky, which can easily be 18 °F (10 °C) below the ambient temperature (Marlo and Berdahl 1984). On a clear night, the roof radiates substantial heat to the sky, lowering T_{roof} well below T_{inlet}. The air entering the building is not as strongly affected by heat loss to the night sky, and thus is often warmer

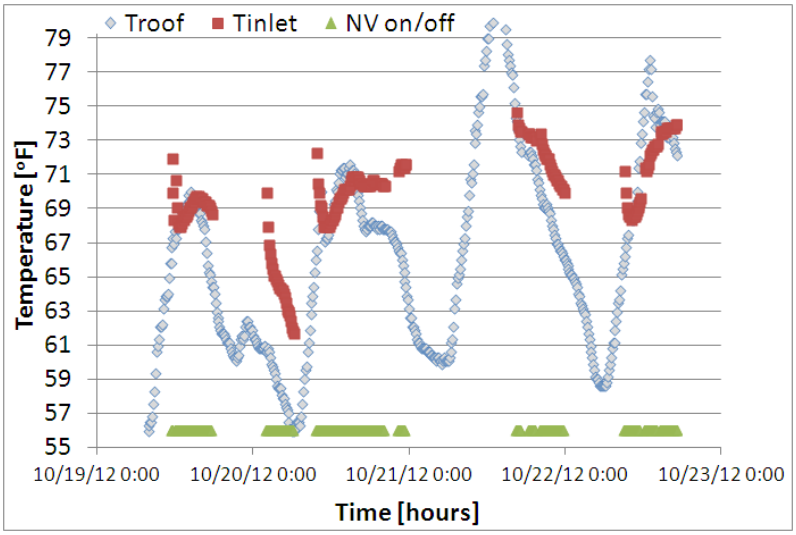

Figure 6 *Measured outdoor temperature from roof-top weather station, T_{roof}, and NV inlet temperature on sixth floor, T_{inlet}, which is only plotted when the NV system was in use, indicated by triangles along bottom of plot.*

Figure 7 *Picture of roof-top weather station used to measure ambient conditions used in the control system.*

than T_{roof}. Ignoring the transition period of T_{inlet} from MV to NV, T_{roof} was up to 6.1 °F (3.4 °C) below T_{inlet} during the morning of October 20. These differences between T_{roof}, the outdoor temperature used in the control algorithm, and T_{inlet}, the measured air temperature that enters the building, indicate that natural ventilation is not fully utilized. Although T_{roof} reasonably approximated T_{inlet} on cloudy days, such as October 19 and 20, the outdoor temperature used in the control algorithm should be measured directly at the façade inlet to more fully utilize the natural ventilation system.

System Interaction

Interconnected systems must be designed and controlled to operate together. For example, the security system and NV system can impact one another as openings controlled by the security system can block airflow paths and openings required for the NV system can pose security threats, especially on lower floors. Figure 8 presents a plan view of the sixth floor and helps illustrate the importance of the proper design and control of interconnected systems. The building core, consisting of three elevators and a stairwell, was designed to be sealed from each floor.

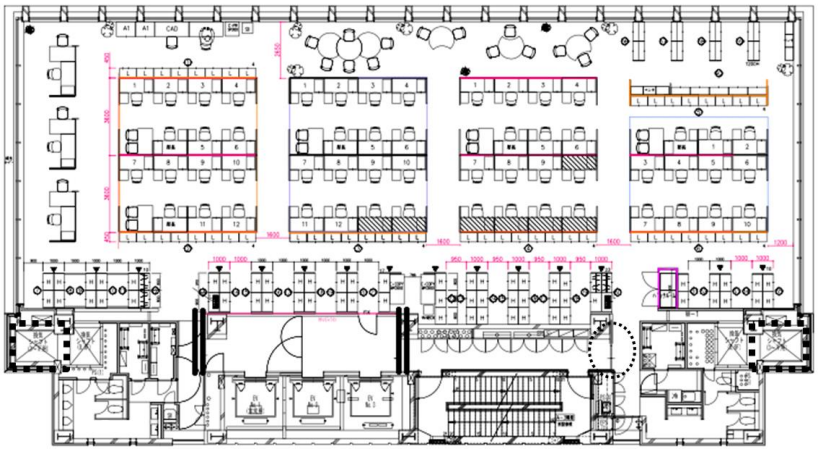

Figure 8 *Plan view of sixth floor with card-access security doors, dark double lines, sliding door that is open during business hours, dotted circle, and ventilation shafts, dotted rectangles.*

The dark double lines on the edge of the elevator lobby are security doors that always require card access and seal off the elevator shafts from each floor. Although the stairwell was initially designed to be separated from each floor, the sliding door indicated by a dotted circle is left open during business hours to promote communication between floors. The open sliding door presents another flow path to the NV system and circumvents designed features of that system on certain floors. An airflow visualization technique utilizing neutrally buoyant bubbles with diameters between 0.051 to 0.15 inches (1.3 to 3.8 mm) has been used to carefully indicate flow direction at the sliding door (SAI Model 5) (Sun and Zhang 2003). Volumetric flow rates were measured at the sliding door and the entrance to each ventilation shaft in accordance with ASHRAE Standard 111-2008 using the equal area method (ASHRAE 2008). Velocity measurements used with Standard 111-2008 were made using a hotwire anemometer with a stated accuracy of +/- 3% +/- 0.049 fps (0.015 m/s).

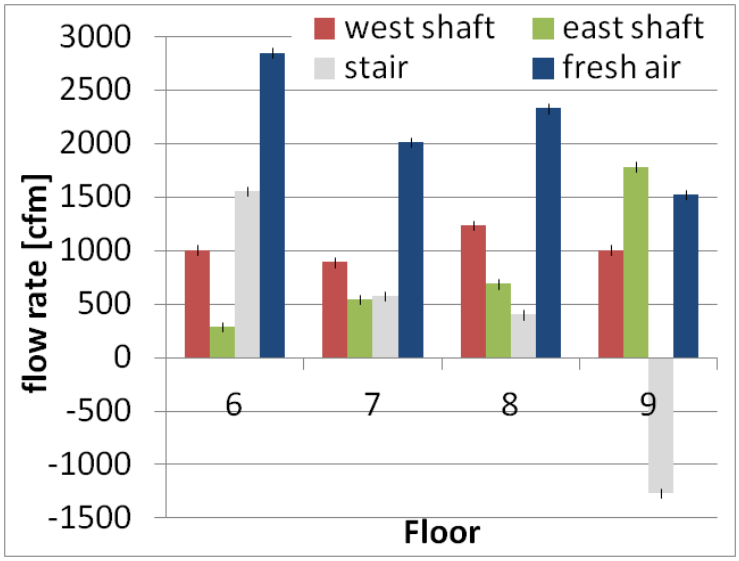

Figure 9 *Measured flow rates to the west and east ventilation shafts and through the sliding door to the stairwell, stair. The total amount of fresh air entering each floor is also plotted.*

Figure 9 plots the measured flow rates at various locations on floors 6-9 taken on October 19, 2012. It reveals a substantial reverse flow from the staircase into the ninth floor, though some of the air that enters the stairwell on lower floors is exhausted elsewhere. Given

the proximity of the sliding door from the stairwell to the east shaft, the dotted rectangle on the right corner of Figure 8, all of the air from the stairwell that entered the ninth floor directly flowed into the east shaft without entering the occupied zone.

The majority of the outdoor air entering the sixth floor was exhausted through the stairwell and not the ventilation shafts because the stairwell offered less flow resistance than the entrance to the shafts (which included a grille, adjustable dampers, and a smaller area than the stairwell). While the NV system provided sufficient fresh air and cooling to the sixth floor, all of the airflow exhausted through the stairwell could not be controlled by the adjustable dampers at the entrance to the shaft. Without this control, too much airflow may have occurred, which could have led to low temperatures that would have caused the control system to turn off NV to mechanically heat the building and unnecessarily use heating energy.

In higher floors, less air was exhausted through the stairwell and was instead exhausted through the east shaft. On the seventh floor, both stairwell and east shaft exhausted approximately the same amount of air, while on the eighth floor, nearly twice as much air was exhausted through the east shaft than through the stairwell. This shift occurred in higher floors because even though there was still less flow resistance through the stairwell, there was a greater driving pressure through the shaft, which led directly to the roof, than through the stairwell, which led to the ninth floor before exhausting to the roof through the east shaft.

Low-power Fan Operation

The low-power fans (1.2 hp (900 W) and 0.60 hp (450 W) for shafts 2-7 and 8-9 respectively) mounted on top of each ventilation shaft were tested over night to easily override the control system and avoid creating uncomfortable indoor conditions during working hours. Tests were designed to answer three questions. First, are the fan speed step sizes large enough to meaningfully increase or decrease flow rates? Second, how uniform are the flow rates from floors 2-7? Third, what happens when only the fans in both 2-7 shafts are on? Will the system perform differently than when all four fans are on, both fans in the 2-7 shafts and both fans in the 8-9 shafts? The same procedure from ASHRAE Standard 111-2008 was used to measure volumetric flow rates at the entrance from each floor to the ventilation shafts and the sliding door to the stairwell was closed. The fan speed was manually increased to the desired step.

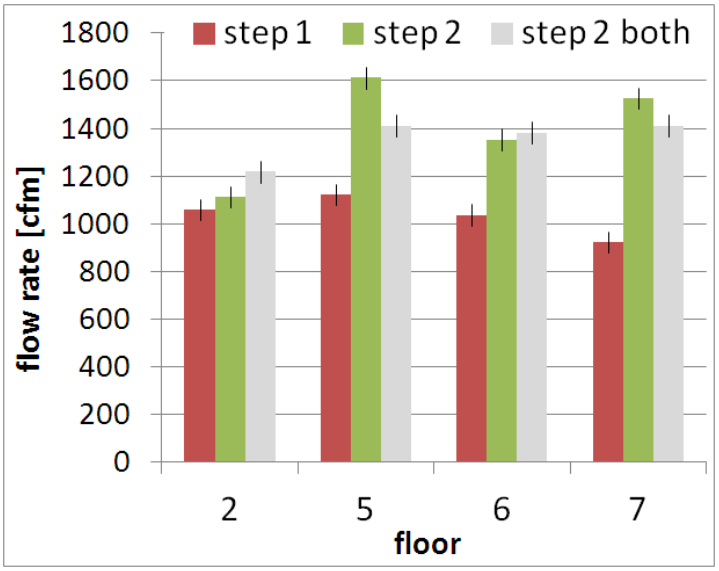

Figure 10 *Measured flow rates in the east ventilation shaft with the 1.2 hp fans running at 2 speeds in both east and west 2-7 shafts, 'step 1' and 'step 2.' 'Step 2 both' was measured with the two 0.60 hp fans in the 8-9 shafts on in addition to the two 1.2 hp fans in shafts 2-7.*

Figure 10 presents the results from the east shaft. Both 'step 1' and 'step 2' were run with only the two 1.2 hp (900 W) fans (one in the east and one in the west 2-7 shaft). The 'step 2 both' label indicates tests that were conducted with the two 1.2 hp fans and the two 0.60 hp (450 W) fans (one in the east and one in the west 8-9 shaft). The fan step size was large enough to increase flow rates on all floors, although only slightly on the second floor. This slight increase was likely because the second floor is eight floors away from the fan, which is mounted just above the tenth floor. Flow rates were fairly uniform, having the largest difference between any two floors for 'step 1,' 'step 2,' and 'step 2 both' of 18%, 31%, and 14% respectively. Finally, the system appeared to behave similarly when only the 1.2 hp (900 W) fans were used and when all four fans were used. No reverse flow was observed on any floor when only the 1.2 hp (900 W) fans were used, which was a potential concern given the 0.16 inches H_2O (40 Pa) pressure rise of the fans and the proximity of the ninth floor to this

region of relatively high pressure. The driving pressure of the natural ventilation system is on the order of 0.04 inches H_2O (10 Pa). Furthermore, the greatest difference in flow rates between 'step 2' and 'step 2 both' was 13% on the fifth floor.

LESSONS LEARNED

The following lessons have been learned through the presented measurements of this hybrid ventilation system:

1. In a well designed, open-plan office with hybrid ventilation, most of the air at desk level within the occupied zone is at a fairly uniform temperature. When NV was used, the maximum average difference between any two points was 1.5 ^oF (0.83 ^oC). This difference decreased to 0.98 ^oF (0.54 ^oC) when mechanical ventilation and cooling was used.
2. Use the measured inlet temperature instead of a roof-top weather station measurement for the outdoor air temperature in a control algorithm to fully utilize the energy saving potential of a hybrid ventilation system. Otherwise, the rooftop temperature may differ up to 6.1 ^oF (3.4 ^oC) in the fall during a sunny day or clear night.
3. Discuss the exact location of each sensor that provides input to the control system to ensure it provides both accurate and the desired information.
4. Promote constant communication between various design teams, especially for those working on the hybrid ventilation system and the security team.
5. Low-power fans can provide outdoor air to many floors at a fraction of the power required to run the mechanical system if outdoor conditions allow for NV but natural driving forces are insufficient.

In addition to lessons gleaned from the presented measurements, the following lessons have been learned through the design and commissioning of this hybrid ventilation building:

6. Occupants resisted changing to a hybrid system and consistently blamed the NV system for any uncomfortable indoor conditions, even if it had been off all day.
7. The control algorithm required considerable debugging after it was programmed into the building control system. These costs for such a complicated control system should be factored into the cost benefit analysis of the NV system.
8. Extended commissioning of the NV system is highly recommended to ensure all system components work properly and the building control system accurately follows the designed control algorithm. Since the NV system relies on natural driving forces that vary throughout the year, it should be commissioned in each season. Even if it will not be used in the winter, the NV system should be inspected to ensure all openings are properly sealed and remain closed and that no unexpected drafts occur in the building due to airflow paths.

ACKNOWLEDGMENTS

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REFERENCES

ASHRAE. 2008. Standard 111-2008: Measurement, Testing, Adjusting, and Balancing of Building HVAC Systems. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

ASHRAE. 2010. Standard 55-2010: Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

Marlo, M and Berdahl, P. 1984. Characteristics of infrared sky radiation in the United States. Solar Energy, 33: 321-336.

SAI Model 5 Console. http://www.sageaction.com/

Sun, Y and Zhang, Y. 2003. Development of a stereoscopic particle image velocimetry system for full-scale room airflow studies, part II: experimental setup. ASHRAE Transactions, 109(2).