Title
Mixed-mode ventilation: Hvac meets Mother Nature

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Although more complex to design, combining operable windows with traditional systems can reduce energy use. It can also increase individual climate control, which has multiple benefits of its own. Europe and Japan are implementing mixed-mode already, and it may be coming to an office building near you in the future.

BY GAIL S. BRAGER, PH.D.,
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Ask anybody you know if they would prefer to have an operable window in their office, and chances are you'll find few people who would say "no." So why are so many office buildings designed with sealed glass facades that don't allow occupants to open a window and get a (real or imagined) "breath of fresh air"? Has our culture become addicted to air conditioning? How can we encourage engineers to be truly innovative, to move beyond conventional practice by designing or retrofitting buildings that provide the benefits of both natural ventilation and air conditioning?

Most contemporary office buildings are designed with sealed envelopes, are internal-load dominated, and are cooled by mechanical air conditioning systems. The hvac system is designed to maintain constant, uniform conditions throughout the interior, but at a significant cost in terms of capital, energy consumption, and associated environmental impact. Mechanical cooling and fan energy accounts for approximately 20% of commercial building electrical consumption in the United States.

Furthermore, occupants have little opportunity to adjust the systems for their personal comfort preferences (which can vary significantly), leaving the centralized controls to satisfy, at best, only a percentage of the occupants at any one time. It is, therefore, no surprise that many studies have found that the top complaint in office buildings is typically related to thermal comfort.

In contrast, naturally ventilated buildings are generally skin-load dominated, rely on operable windows for both ventilation and cooling, and require user interaction to maintain comfort conditions in the building. Naturally ventilated buildings tend to use much less energy than air-conditioned buildings. Occupants often have significant control over their personal comfort conditions, and there is a distinct connection between the outdoor and indoor environments. The thermal environments in naturally ventilated buildings are typically more variable and less predictable than those found in air-conditioned buildings, but not necessarily less comfortable.

Recent ASHRAE-sponsored research conducted by co-author Dr. Gail Brager demonstrated that occupants of naturally ventilated buildings are comfortable over a much wider range of temperatures compared to occupants of air-conditioned buildings, primarily because the higher degree of personal control shifts their expectations and preferences. The next revision of ASHRAE Standard 55 will incorporate a new "adaptive model" of thermal comfort based on this research, but as yet it will only be applicable to naturally ventilated buildings without mechanical cooling systems.

While nearly all engineers would probably agree that occupants prefer operable windows, most of them are unwilling to relinquish the tight control over interior temperatures that a mechanical system provides. So why not use both, and design a "mixed mode" building?

WHAT IS A MIXED-MODE BUILDING?

Mixed-mode refers to a hybrid approach to space conditioning that combines natural ventilation with mechanical ventilation and cooling. A well-designed, mixed-mode building often incorporates sophisticated controls that allow the build-

Hvac meets Mother Nature

The test building in Palo Alto, CA uses a VAV system and allows individual control of thermostats. With its "changeover"system, micro-switch sensors in the windows shut off a zone VAV box if the corresponding window is open.

ing to alternate between these two modes during different times of the day or season, to maximize comfort while avoiding the significant energy use and operating costs of year-round air conditioning.

Mixed-mode is appropriate both for the design of new buildings, as well as the retrofit of air conditioning into older naturally ventilated buildings in which internal gains have increased significantly due to higher occupant densities or equipment loads. Mixed-mode cooling and ventilation is most applicable for relatively small, low- and medium-rise commercial buildings in temperate climate zones, where mechanical cooling may be necessary only a small fraction of the year.

In these situations, natural ventilation has clear advantages over air conditioning, yet air conditioning may be desirable to address seasonal peak cooling loads and/or highly loaded zones. Table 1 contrasts typical approaches to naturally ventilated, air-conditioned, and mixed-mode buildings for several key building design issues.

Mixed-mode cooling strategies can take many forms, but generally will involve an intelligent control strategy and a building envelope that becomes a critical part of the system. William Bordass has created a useful taxonomy of mixed-mode strategies, as shown in Table 2, based on a classification scheme originally proposed by Max Fordham Partners.

Concurrent mixed-mode operation with occupant-controlled operable windows is the most prevalent design strategy in practice today, although changeover and zoned mixed-mode designs are becoming increasingly common. Changeover and concurrent systems perhaps offer the greatest potential for gaining "the best of all worlds" by mixing the different ventilation and cooling strategies in the same space at the same time. These systems, however, may also yield "the worst of all worlds" if air conditioning and natural ventilation systems are not coordinated in an efficient manner that is understandable to occupants, operators, and automated control systems.

There does not seem to be a "standard" mixed-mode approach in practice today – each building continues to be unique. For many mixed-mode buildings, operating conditions have deviated somewhat from their original design intent (e.g. a building originally designed for seasonal changeover between air conditioning and natural ventilation may, in practice, operate both systems concurrently).

POTENTIAL BENEFITS

Mixed-mode buildings offer three broad advantages over sealed-air conditioned buildings:

Reduced hvac energy consumption. A well-designed and properly operated mixed-mode building can scale back or eliminate the use of mechanical cooling and ventilation systems throughout much of the year, with associated reductions in pollution, greenhouse gas emissions, and operating costs. Ventilation with cool outside air can reduce a commercial building's energy use by 15% to 80%, depending on climate, cooling loads, and building type. Concurrent mixed-mode schemes, however, may result in wasted energy if air conditioning and natural ventilation conflict with one another.

Higher occupant satisfaction. Mixed-mode buildings generally offer occupants higher degrees of control over their local thermal and ventilation conditions, which should lead to increased occupant satisfaction and reduced potential for IAQ problems. Several researchers have found that building occupants are more tolerant of fluctuations in interior conditions when they are provided with some measure of personal control. Under some conditions, however, natural ventilation may be undesirable due to airborne pollutants and allergens, or outdoor noises.

Highly "tunable" buildings. Mixed-mode strategies provide inherent flexibility and redundancy in the space conditioning systems of a building, resulting in potentially longer life, greater adaptability to changing uses, and reduced lifecycle costs. With the careful application of mixed-mode cooling and ventilation, one can anticipate somewhat smaller mechanical systems and extended hvac equipment life.

BARRIERS TO THE APPROACH

Over the last 10 years, an increasing number of office buildings have successfully integrated air conditioning and natural ventilation, particularly in continental Europe, the United Kingdom, and Japan. Given the potential benefits of mixed-mode cooling strategies, the question remains: Why aren't we seeing more of these buildings in the United States? There are several potential barriers (real and perceived) to more widespread adoption of mixed-mode schemes. The problems we have identified fall into the following four inclusive categories.

Building Design Issues. The U.S. building design industry is generally unfamiliar with mixed-mode cooling strategies, and there is a lack of available design tools and case studies to facilitate their education. Existing design standards (particularly ASHRAE Standards 62 and 55) leave little flexibility for unconventional or innovative hvac designs.

Building Operations and Controls Issues. Mixed-mode build-

Hvac meets Mother Nature

	Naturally Ventilated (NV)	Air Conditioned (AC)	Mixed-Mode (MM)
Building Form	Small floorplates, which allow for cross-ventilation and generous ceiling heights are typical.	Large floorplates with relatively low ceiling heights are often preferred.	A plan depth of no more than 15 m (45 ft) is recommended to take full advantage of natural ventilation.
Building Envelope	The mass of the building fabric and structure helps to dampen diurnal temperature swings. External shading is used for solar control.	Envelope is relatively lightweight and designed to be tightly sealed. Tinted glazing is used in lieu of external shading to control solar heat gain.	Thermal mass in the building envelope and structure should be used to dampen daily temperature swings. External shading is preferred.
Windows & Lighting	Windows are relatively small and are operable. Daylighting is preferred to avoid internal heat gains associated with artificial lighting.	Glazing is sealed and often deeply tinted to limit solar heat gain. High glass-to-wall ratios are typical. Fluorescent lighting is standard.	Windows are operable and may include both automatic and occupant control. Window design and controls are more complex than NV or AC.
System Controls	Control of indoor conditions is dependent on occupant behavior. Occupants must both respond to and predict outdoor conditions in determining how much to ventilate the building.	Hvac controls may be complex and are generally handled by automated systems, using feedback control. System operators play a key role in maintaining the system.	Control may be a synthesis of occupant and automatic control systems. Both feedback (responsive) and feed-forward (predictive) strategies should be employed.
Occupant Comfort	Occupant comfort is largely dependent on external conditions, which may vary significantly seasonally and daily.	Hvac system strives to maintain uniform thermal conditions. Occupant comfort is closely linked to hvac system performance.	Occupants have control with a/c system providing “background” cooling and ventilation. AC provides relief if NV system fails (or vice-versa).
Ventilation Rate & IAQ	Ventilation rates are very high during temperate and warm outdoor conditions. IAQ is rarely a problem.	Ventilation rate is often fixed in a minimal position. Hvac system may cause IAQ problems if not maintained properly.	On average, ventilation rate will be somewhat higher than AC bldgs. NV can provide quick relief if IAQ problems emerge.
Hvac Energy	Relatively little hvac energy is consumed.	Hvac energy use varies depending on system design and operation. Often systems operate inefficiently for extended periods with little or no correction.	Hvac energy use should be less than AC buildings. Energy may be wasted, however, if NV and AC systems are not carefully coordinated.

TABLE 1. Characteristics of typical naturally ventilated, air conditioned, and mixed-mode buildings.

Hvac meets Mother Nature

Occupants in this 208,000-sq-ft facility in Sacramento, CA may have the most "sophisticated" of the three systems. It employs a "changeover" system that reacts when windows are open; workers also enjoy the flexibility of reconfigurable floor air diffusers.

ings may require integrating automatic and manual control strategies for both hvac and building fenestration systems, which can be significantly complex. Commercial building designers and operators also share a general lack of familiarity with operable windows (and other permeable building envelopes) and a concern about their associated maintenance requirements.

Fire and Safety Concerns. The potential for smoke migration in a commercial building designed to incorporate wind-driven or stack-driven ventilation is at odds with many local building codes. There may be further concerns about building security and occupant safety for commercial buildings with operable windows.

Energy Code Concerns. California Title-24 and other energy codes tend to limit designers to fairly conventional hvac systems. Standards generally frown upon installing operable windows and mechanical cooling systems for the same zone.

STUDYING AT HOME AND ABROAD

In recent years, the international building industry has focused more attention on buildings explicitly intended to operate as mixed-mode, or what is also referred to as "hybrid ventilation." In 1999, The International Energy Association (IEA, *http://hybvent.civil.auc.dk*) launched a three-year "research annex" to develop control strategies and performance prediction methods for hybrid ventilation in new and retrofitted buildings. Participants from 15 countries are carrying out research on control strategies and analysis methods, and conducting field studies of existing mixed-mode buildings to investigate their IAQ, thermal comfort, and energy consumption. The main objectives of the project are:

- To develop control strategies for hybrid ventilation systems in new and retrofitted office and educational buildings;
- To develop methods to predict ventilation performance in hybrid ventilated buildings;
- To promote energy and cost-effective hybrid ventilation systems in office and educational buildings; and
- To select suitable measurement techniques for diagnostic purposes to be used in buildings with hybrid ventilation systems.

Recognizing that the U.S. building industry has not yet widely embraced mixed-mode strategies, the Center for the Built Environment (CBE, a university-industry collaborative research center located at the University of California, Berkeley) has undertaken research to find out what makes a mixed-mode building successful and what designers can do to implement cost-effective, energy-efficient, and user-friendly mixed-mode strategies. The research is ongoing, and the full results will be available from CBE in fall 2000. However, we can briefly summarize the nature of the project and some of the key findings here.

Methods. This project focused on investigating occupant comfort, control, and satisfaction in three mixed-mode office buildings located in Northern California's temperate climate. At each site, CBE administered an occupant survey and interviewed the architects, engineers, and facility managers to learn about how each building operates and how well it lives up to occupants' expectations. The web-based survey is based on the "Indoor Environmental Quality Assessment" tool that CBE has developed for benchmarking how satisfied occupants are with various aspects of their indoor environment (*www.cbe.berkeley.edu/survey*).

The survey includes questions about satisfaction with various aspects of the indoor environment, as well as access, use patterns, and satisfaction with operable windows and personal hvac controls. The survey is announced via e-mail and filled out by building occupants online through their web browser. Survey responses and comments are then recorded anonymously in a database maintained by CBE.

Research sites. All three buildings were built in the 1990s and include air conditioning systems and occupant-controlled operable windows. They range in size from 75,000 to 200,000 sq ft, and they are unique in terms of the design of their hvac systems, space layout, and organizational culture. Two of the buildings allowed occupants to control the thermostats, while the third provided occupant control of floor air diffusers. Two of the buildings could be classified as "changeover" schemes, where micro-switch sensors in the windows shut off a zone VAV box if the window is open. The third

This test building is located in San Rafael, CA. The smallest of the test buildings (75,000 sq ft), it operates a "concurrent" system, so that the status of windows had no effect on the mechanical system operation.

I. Contingency	Building is designed either as an air conditioned (AC) building with provisions to convert to natural ventilation (NV) or as an NV building with space allocated for future installation of a/c equipment. Can be used when designer anticipates significant changes in the future building use. Contingency mixed-mode (MM) designs are very rare.
II. Zoned	Different zones within the building have different conditioning strategies. Many buildings, both old and new, can be classified as zoned MM schemes. Typical examples: Naturally ventilated office building with operable windows and a ducted heating/ventilation system, and supplemental mechanical cooling provided only to conference rooms.
III. Complementary	Building is designed with AC and NV capability in the same spaces. This category is further subdivided into Alternate, Changeover, and Concurrent MM strategies, as described below.
A. Alternate	Building includes provisions and equipment for both AC and NV but operates indefinitely in one mode or the other. Like Contingency, this strategy is very uncommon and only applicable in situations where significant changes in the building use are anticipated.
B. Changeover	Building "changes-over" between NV and AC on a seasonal or even daily basis. The building automation system may determine the mode of operating (AC or NV) based on outdoor temperature, an occupancy sensor, a window (open or closed) sensor, or based on operator commands. Typical examples: Individual offices with operable windows and personal air conditioning units that shut down for a given office anytime a sensor indicates that a window has been opened; or a building envelope where automatic louvers open to provide natural ventilation when the hvac system is in economizer mode, and then close when the system is in cooling or heating mode.
C. Concurrent	AC system and NV provisions operate in the same space and at the same time. Hvac system may serve as supplemental or "background" ventilation and cooling while occupants are free to open windows based on individual preference. Typical example: Open-plan office space with standard VAV air-conditioning systems and operable windows. Perimeter VAV zones go to minimum air when sensor indicates that a window has been opened.

TABLE 2. Classifications of mixed-mode strategies (as originally proposed by Bill Bordass, based on toxonomy by Max Fordham).

building could be characterized as a “concurrent” scheme, since opening and closing the windows have no direct impact on the operation of the mechanical system.

Key findings. Some key findings include the following: Frequency of use of windows was influenced by ease of access (related to interior space planning, the window handles, and the placement of desks and partitions), outdoor climate, organizational culture, and availability of alternative control over the hvac system.

The most frequently offered reason for why people open their windows was “to bring in fresh air,” followed by “to create more air movement,” and then “workspace too warm.”

The most frequently offered reasons for why people close their windows was “outdoor noise,” followed by “workspace too cool,” “too much air movement,” and “outdoor dust, dirt, and odors.”

There was a strong correlation between having access to operable windows and satisfaction with air movement, ventilation, and air quality. The correlation was not as strong for satisfaction with temperature. These patterns were slightly different in the three buildings, however, and need to be investigated in more detail.

The building that offered the highest degree of control (i.e., highest percentage of people with easy access to windows and thermostats in every office) produced the highest levels of occupant satisfaction with nearly every aspect of the indoor environment (temperature, air movement, ventilation, humidity, and odors). This trend was particularly strong for temperature satisfaction. It is likely that a responsive facility management team that addressed thermal comfort complaints quickly also influenced this pattern.

When occupants had access to both hvac controls (thermostats or floor diffusers) and operable windows, they tended to be more satisfied with the windows, and also use them more often, as compared to the hvac controls.

CONCLUSIONS

Mixed-mode buildings offer great promise for reducing energy operating costs while maximizing comfort and providing occupants with a sense of personal control and connection to the outdoors. Other potential advantages include reduced lifecycle costs and increased flexibility and adaptability of building use. Although mixed-mode buildings are becoming increasingly popular in Europe and Japan, there are relatively few examples in the United States. What can we do within both the research and engineering communities to encourage the more widespread adoption of this innovative design strategy, and overcome the many barriers that exist? We feel that the following activities are needed:

- Theoretical and experimental research to quantify the benefits of mixed-mode building;
- Building energy simulations to evaluate the energy savings potential for mixed-mode buildings in different climate zones;
- Detailed field studies which combine subjective surveys with field measurements of thermal conditions and ventilation levels in mixed-mode buildings;
- Development of design tools and guidelines;
- Revisions of ASHRAE Standards 55, 62, and 90.1 to encourage more alternative environmental control strategies; and
- Greater collaboration between researchers and the professional community. ES

Brager, Ph.D., is an associate professor in the Department of Architecture at UC Berkeley, where she is also the associate director of the Center for the Built Environment. In addition to her teaching and research with CBE, she stays active in ASHRAE research on thermal comfort and serves on the committee to revise ASHRAE Standard 55.

Ring completed his M.S. degree in the Department of Architecture at UC Berkeley in May 2000. The work described in this paper formed the nucleus of his Masters thesis. He is currently working as a mechanical engineer in the sustainability specialty group at Syska & Hennessy (Los Angeles).

Powell is the executive director of the Center for the Built Environment, coordinating the efforts of its researchers and serving as a liaison between the university and CBE's partners. Reach him at **Kpowell@uclink4.berkeley.edu**.

Interesting times at the CBE

The Center for the Built Environment (CBE) was established in May 1997 at the University of California, Berkeley. The research is funded by annual contributions from industry partners, while the National Science Foundation underwrites the administrative costs. The goal is to provide timely, unbiased information on promising new building technologies, operating strategies, and design techniques.

Currently there are 15 industry partners participating in CBE: Armstrong World Industries; California Department of General Services; California Energy Commission; Henningson, Durham & Richardson (HDR); International Facility Management Association (IFMA); Johnson Controls; Lucent Technologies; Ove Arup & Partners; Pacific Gas & Electric Co.; Skidmore, Owings & Merrill (SOM); Tate Access Floors; U.S. Department of Energy (DOE); U.S. General Services Administration (GSA); York International Corporation (York, PA); and a Webcor Builders Team that includes its subcontractors Alfa Tech Consulting Engineers, Critchfield Mechanical, and Rosendin Electric. This diverse set of industry partners has a common interest in sharing information on improving the design and operation of commercial buildings. Industry partners help direct CBE research and get early access to research progress and findings.

Faculty, research staff, and graduate students in the Building Science Group within the Department of Architecture at UC Berkeley conduct the majority of CBE's research. The core research staff includes a mix of engineers and architects with a wide variety of academic research, applied research, and other professional experience. CBE also has affiliated faculty in other departments at UC Berkeley, at other universities, and at Lawrence Berkeley National Laboratory.

CBE focuses its research into two broad categories concerning commercial buildings:

Tools for Improved Building Performance: Research methods that “take the pulse” of operating buildings —- looking at how people use space, asking them what they like and do not like about the interior environment, and linking these responses to physical measurements of indoor environmental quality.

New Building Technologies and Design Strategies: Research on how designers can make buildings more environmentally friendly, more productive to work in, and more economical to operate.

There are currently seven ongoing CBE research projects, and a host of smaller, short-term efforts. Three of the current projects are developing new tools for improved building performance. They address improving the occupant feedback process, benchmarking IAQ levels, and the correlation between ventilation control and occupant productivity. The remaining four projects are exploring emerging building technologies and design strategies. These include underfloor and task/ambient systems along with the study of team space design and use, as well as the mixed-mode concept.