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From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review

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ABSTRACT

The energy required to maintain comfortable indoor environmental conditions is a significant percentage (35%) of the overall energy consumption in office buildings. In the modern-day realization of climate change and global warming potential, the reduction of energy consumption in office buildings (particularly energy consumed using cooling and mechanical ventilation systems) and maintaining indoor environmental conditions, is an essential design requirement particularly for buildings located in hot, arid climates. The mixed-mode ventilation (MMV) strategies have been effectively used in the past for saving energy as well as maintaining indoor air quality for the occupants by sustaining adequate indoor environmental conditions. It has been found that mixed-mode buildings have the potential to save 40% HVAC energy by optimizing window operation schedules, and up to 75% by alternating natural and mechanical ventilation. However, to successfully optimize these strategies, it is imperative to understand what factors affect the performance of mixed-mode buildings in terms of energy savings and comfort of the occupants. A comprehensive literature review was conducted covering the past two decades (1996–2016) to analyze the use of MMV systems in office buildings. The study provides the reader with an impression of which practical objectives have been pursued, what progress has been made in the past two decades, and what the future challenges are for using MMV systems in office buildings.

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1. Introduction

In most of the developed as well as developing countries, the non-residential buildings account for a substantial percentage of the overall energy demands [1]. In fact, the energy consumed by commercial buildings accounts for over 21% of the total energy consumption in the United States, [2], 35% in India [3], 37% in China, and 46% in the United Kingdom [4] making the building sector one of the largest energy consumers [2]. In the United States, cooling and mechanical ventilation systems in commercial buildings account for over 30% of the total energy consumption in the buildings, 20% of the of the total electricity consumed and 40% of peak electricity demand in the buildings [5]. Also, mechanical ventilation systems account for 31% of the energy used by commercial buildings in India [3]. Air-conditioning and mechanical ventilation systems were developed by a "rich" culture to avoid hot climates at a cost of requiring high-grade fossil fuel consumption [3,6]. In hot climates, air-conditioning is the most used method to maintain the thermal comfort of the occupants inside the building. This conditioning not only consumes an enormous amount of energy, which represents an increased cost associated with the building [7] but also, increases greenhouse gas emissions [8]. In the modern-day realization of climate change and global warming potential, the reduction of energy consumption in buildings and maintaining indoor environmental conditions is an essential design requirement especially in hot, arid climates [1]. As a result, researchers, engineers, and designers are facing new challenges i.e. the reduction in the use of mechanical air-conditioning systems, while maintaining the thermal comfort of the occupants in a building.

Natural air ventilation has the potential to provide good air quality and improve the thermal comfort in hot climates by increasing

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daytime air speed and high night time ventilation rates. Besides, natural air ventilation provides for the possibility to achieve high ventilation rates for cooling purposes without consuming a significant amount of energy [9]. However, in developed countries such as the United States, it is impossible to rely solely on natural ventilation, especially in hot and arid climates. This is a critical design aspect of buildings, especially since the expected satisfaction and thermal comfort of the occupants is a standard requirement (ASHRAE standard 55-2004) [10]. This standard specifies the thermal conditions in which 80% or more of the occupants within a space of a building will find the environment thermally acceptable based on the heat balance model of the human body. This model is influenced by many factors, including environmental factors (temperature, thermal radiation, humidity, and air speed); and personal factors (activity and clothing) [11]. For arid and hot climate conditions in the United States, the use of only natural ventilation has been proven insufficient to be acceptable in terms of inside thermal comfort [12]. The combined utilization of both natural ventilation and mechanical cooling systems in a mixed-mode hybrid ventilation system [13], is a potential solution to provide cooling, air ventilation, Indoor Air Quality (IAQ), and thermal comfort for the occupants inside the building. However, designers of mixed-mode buildings face many challenges.

The MMV strategy is seen as a sustainable way to condition buildings [14], however, this is a relatively new subject area, and so far there is no complete guide on how to simulate and/or design mixed-mode office buildings. It is also important to notice that to date there is no comprehensive state-of-the-art literature review available that provides a complete documentation of MMV strategies, performance, advantages, and disadvantages. This literature review contributes to the understanding of various mixed-mode strategies that have been used in office buildings during the last two decades. Furthermore, a comparison of various studies on how to evaluate and improve natural ventilation in mixed-mode buildings will provide a comprehensive understanding of the benefits and limitations of using operable windows in mixed-mode buildings (Table 1). To date, there are no regulatory standards for the operation or control strategies of mixed-mode buildings. Furthermore, no protocol exists stating the degree of personal or automated control that occupants of the mixed-mode buildings should have. Moreover, the prediction of the performance of these buildings using simulation tools is very sensitive to many design parameters [15]. For instance, Johnson [16] conducted various studies to model three existing naturally ventilated buildings and compared the simulated results with field monitoring data. The results of this study showed several deficiencies of the simulation tools to predict the actual performance of the building. In another study conducted by Coakley et al. [17] simulation tools were used to compare measured performance to the simulated performance of buildings. The results of the study showed a discrepancy between measured and simulated performance. The authors concluded that detailed simulation tools are limited, and it is not possible to accurately predict actual building performance with available software. This literature review evaluated more than ninety research studies and included an in-depth analysis of forty-five articles and reports collected from internationally recognized journals; relevant conference proceedings; as well as selected university theses and study reports that were collected through search engines including ScienceDirect, IEEE Xplore, and Google Scholar. The primary objective of this manuscript was to document, critically analyze, and compare research studies conducted in the past 20 years to demonstrate the efficiency as well as the possible limitations of using the hybrid ventilation strategy known as “mixed-ventilation system” in office buildings. Moreover, the review also provided information regarding current challenges that designers, as well as researchers, are facing to optimize the energy utilization in office buildings while maintaining IAQ and indoor thermal comfort.

The paper is organized as follows: section 2 describes in detail the design characteristics of hybrid ventilation systems, giving emphasis to MMV system; section 3 provides an in-depth evaluation of the past research studies that investigate natural ventilation strategies and their effects on mixed-mode buildings; section 4 describes different mechanical systems used in mixed-mode buildings and provides a review of various studies that compared these systems in terms of energy efficiency, and occupant thermal comfort. Additionally, in this section, efforts to improve the efficiency of mixed-mode mechanical systems are described by analyzing the natural and mechanical ventilation systems used in mixed-mode buildings; section 5 elaborates the limitations of previous research work, presents an overview of the future challenges, and suggestions for potential future work to increase energy efficiency in mixed-mode commercial buildings while maintaining indoor thermal comfort for the occupants.

2. Hybrid ventilation systems

As defined by Wouters et al. [18], a hybrid ventilation system can be described as a ventilation system that provides a comfortable internal environment (IAQ and thermal comfort) using both natural ventilation and mechanical systems at different times of the day and/or season of the year. The primary distinction between conventional ventilation systems and hybrid systems resides in the fact that the second is an intelligent system that can manually or automatically shift from natural ventilation to mechanical ventilation mode for reducing energy consumption in addition to maintaining acceptable indoor environment thermal conditions. Although many research studies have demonstrated positive results by using hybrid ventilation systems in office buildings [11,12,14,18–23], occupants of these buildings may still expect variations from the predicted thermal comfort levels. Furthermore, designers are required to understand that a different design philosophy is required as compared to merely mechanically ventilated buildings since the early design stages to reduce the energy consumption in MMV buildings [19]. In the past, researchers and engineers have explored an innovative hybrid ventilation approach known as MMV system as a way to combine natural ventilation from manually or automatically operable windows and mechanical systems that include air distribution and air conditioning equipment.

Due to increased concerns for enhancing energy efficiency and the necessity to pursue more passive strategies for thermal comfort, new alternative design strategies discourage the use of mechanical cooling systems in situations when natural air can be utilized. However, past research studies have demonstrated that the use of solely natural ventilation leads to the discomfort of the occupants of such buildings especially in extreme weather conditions [24]. For this reason, the use of a type of hybrid ventilation system known as “mixed-mode” has been evaluated and extensively used in recent years. The MMV system refers to a hybrid ventilation approach to space conditioning employing the combination of natural ventilation from manually or automatically controlled windows and mechanical air conditioning that provide air distribution and a form of cooling when necessary [25]. Some other kinds of ventilation modes used in MMV systems may be ventilation assisted by low-power fans and passive inlet vents [13,22,27]. The primary goal of MMV buildings is to maximize the building’s internal thermal comfort avoiding the unnecessary use of energy from year-round mechanical air conditioning [28].

The Center for the Built Environment (CBE) at The University of California developed a summary report to describe and understand

Table 1
Major research developments (2000–2016) that describe the implementation and effectiveness of MMV systems.

Item	Reference	Objectives	Method	Climate zone	Significant findings
Mixed-mode description and effectiveness	Ring 2000 [29] Brager et al. [5]	Defined characteristics of mix-mode buildings.	Report	N/A	Described features of mix-mode buildings including reqd. plan depth, thermal mass, ventilation rates, control of the indoor conditions, windows control and occupants control
	Barlow and Fiala [30]	Studied the thermal sensations, assessment of lighting and air movement, perceptions of comfort, and reactions of occupants	On-site surveys	Oceanic climate	The building occupants voted positively for active adaptive opportunities
	Spindler and Norford [26,27]	Developed building thermal predictions from data- driven thermal model	Computer simulations	Humid continental	Developed means of ranking and choosing among a set of cooling strategies for maintaining occupied-period temperatures within a specified range and minimizing fan energy use.
	Deuble and de Dear [31]	Investigated how MMV affects the occupant comfort in office buildings	On-site measurements and surveys	Moderate sub-tropical	MMV strategies ensure comfortable conditions for the occupants
	The Center for the Built Environment (CBE) [28].	Developed a summary report to describe and understand the operational control strategies for mixed-mode buildings.	Summary report		Classification of mixed-mode buildings in terms of their operation strategies.
	Honnekeri et al. [32]	Captured the "right-now' opinion of the indoor environmental quality such as thermal and humidity sensation, air movement and comfort of the occupants.	On-site observations and Surveys	Hot and dry	Occupants, in mixed-mode buildings, prefer to have air movement in their personal space and that 80% of the occupants of the building were satisfied with the temperature of the building at all times.
	Alessi et al. [33]	Conducted a study to understand the thermoregulatory behavior in a mixed-mode environment	On-site measurements, observations, and surveys	Oceanic climate	The results showed that occupants feel comfortable in the mixed-mode space of the building in autumn and spring with a high level of acceptability of the thermal environment throughout the year.
	Luo et al. [34]	Examined occupants' thermal comfort responses in mixed-mode buildings	On-site measurements	subtropical climate	The findings provided support for a more flexible applicability of the adaptive comfort model in the real world.
	De Vecchi et al. [35]	Studied the connection between prior exposure to air-conditioning spaces and its implications for occupants' overall thermal comfort in mixed-mode buildings.	On-site measurements and questionnaires	Subtropical climate	Occupants' history of prior exposure to air conditioning influenced their overall thermal comfort and cooling preferences. However, there is a significant potential to implement temperature fluctuations indoors especially when designing and operating mixed-mode buildings in warm climates.
	Manu et al. [3]	Conducted field surveys in 16 buildings to capture the "right-here-right-now" thermal comfort opinion of occupants	On-site observations and Surveys	5 different climate zones	Occupants felt "neutral" in their environment suggesting that people can effectively adapt to possible higher indoor temperatures in mixed-mode buildings.

the operational control strategies for mixed-mode buildings [28]. The report provides details of the standard classification of mix-mode buildings in terms of their operation strategies that define whether the natural ventilation and mechanical cooling are operating in the same or different areas, and/or at different times of the day or season. According to the report, mix-mode ventilation systems in buildings can be classified as follows: (1) concurrent (same space, same time) mixed-mode design system that is a type of mixed-mode operation system where the mechanical cooling and natural ventilation can operate in the same space at the same time. The Heating, Ventilating, and Air Conditioning (HVAC) system is used only as an additional ventilation tool in case the occupants do not feel entirely satisfied with the ventilation and/or thermal conditions of the building from the exposure to natural air from the open windows are not satisfactory; (2) change-over (same space, different times) mixed mode design system which is a type of mixed-mode operation system where the building interchanges mode of cooling and ventilation between natural ventilation from operable windows and mechanical cooling from HVAC on a seasonal or everyday basis, as necessary. This system requires an automation system to determine what mode should be used at any time of the day based on the outdoor temperature and occupancy.

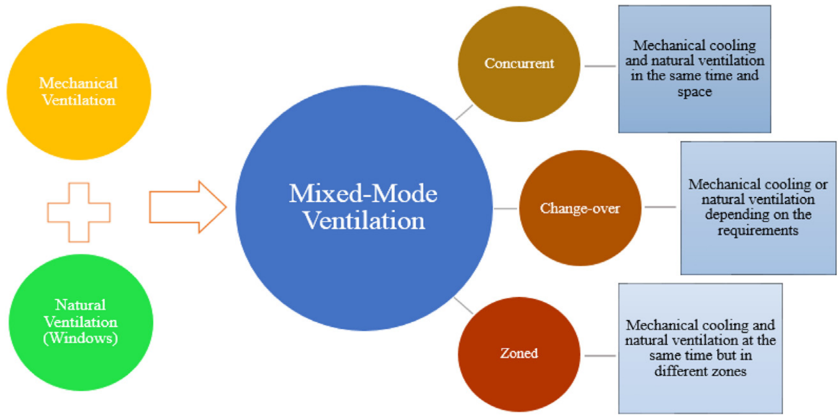

Fig. 1. Types of MMV systems.

These automation systems alert the occupants of the building to open or close the windows, or the mechanical air-conditioning system depending on the operating system required at any time of the day; (3) zoned (different spaces, same time) mixed mode design system which is a type of mixed mode system where the mechanical cooling and natural ventilation operate in different areas of the building at the same time. Fig. 1 shows the classification process for MMV buildings based on the use of operable windows and/or mechanically assisted ventilation (Fig. 1).

MMV buildings require the use of automatic controls or occupant controlled strategies for the system to properly function. The strategies that propose schedules to open windows are based on multiple factors such as occupancy of the building [36–38], outside temperatures [39,40], and the necessity to improve indoor air quality inside the building [41,42]. These natural ventilation strategies, together with schedules for the mechanical systems, must be correctly designed with the goal to assure thermal comfort, air quality, and reduction in the mechanical cooling energy consumption in mixed-mode buildings.

3. Natural ventilation control strategies in mixed-mode buildings

One of the main design characteristics that are currently the focus of research in MMV building is the behavior of the occupants of the building in using manual or automatic windows for natural ventilation controls. In fact, numerous studies have been conducted to predict the occupant behavior in the buildings to design the most appropriate windows characteristics and provide thermal comfort for most of the occupants of the building along with saving energy as well as maintaining indoor air quality.

3.1. Impact of window operation on MMV building performance

The mode of operation of windows has a substantial impact on the indoor environment and overall cooling/ventilation energy consumption in MMV buildings [43]. Many studies over the past two decades have been dedicated to investigating what is the impact of windows operation variations in MMV buildings. Wang and Chen [44] studied the effects of the window opening area on the electricity saving potential of MMV buildings using CAV cooling systems along with natural ventilation from operable windows. During the research, a building with a floor area of 600 sq. meters and with a total of 18 sq. meters of window area was simulated using the EnergyPlus software [45] under two different scenarios: (1) building without thermal mass, and (2) building with 200 millimeters of concrete to provide thermal mass for the exterior walls and floor slab. Furthermore, these simulations considered: (1) fully open window area; (2) half-open window area; and (3) one-quarter open window area. These simulations were performed under three different climates i.e. hot and dry, marine, and warm and humid. The results showed that one-quarter of open window area is optimum to provide the maximum energy savings (62.77%–71.8%) in marine climates for buildings with or without thermal mass. In hot and dry climates the optimum window opening area to provide maximum energy savings is half open for buildings without thermal mass (24.65%) and fully open for buildings with thermal mass (47.9%). Finally, in warm and humid climates the optimum window opening area to provide maximum energy savings (10.5%–19.7%) is half open for buildings with or without thermal mass in MMV buildings.

Most recently, Wand and Greenberg [43] investigated the impact of window operation on the building performance for different types of ventilation systems including natural ventilation, MMV (change-over and concurrent), and conventional VAV systems in an office building designed to comply with ASHRAE 90.1. In the changeover MMV strategy, whenever a window in a perimeter zone of the building was opened, the VAV system would turn off. For the concurrent MMV strategy, natural ventilation from open windows was taken as the priority source to provide cooling for the perimeter zones of the building, and a mechanical VAV system provided supplemental cooling when natural ventilation alone was not enough to meet cooling set points. For the study, the EnergyPlus software [45] was utilized to simulate building and window operation for three different climates (i.e. humid continental, humid subtropical and Mediterranean mild climate). The results demonstrated that natural ventilation provides the largest saving potential but at a cost of higher unmet hours of thermal comfort for the occupants of the buildings. Fig. 2 shows the results of maximum energy savings achieved by optimizing the window operation in mixed-mode buildings located in different climate zones in studies conducted by Wang and Chen [44] and Wand and Greenberg [43].

3.2. Control strategies

3.2.1. Manual control: advantages and challenges

Windows are the primary control by which the occupants can maintain their indoor environment in MMV buildings [46]. In mix-mode ventilation buildings, the occupants are usually responsible for controlling their indoor environment according to their preferences and the ventilation/cooling requirements of the building. Brager et al. [47] investigated how "occupant operable windows" affect the indoor thermal environment and occupant comfort in an MMV building. The results indicated that occupants in a mixed-mode building experienced surprisingly similar thermal conditions; independent of the proximity and degree of personal

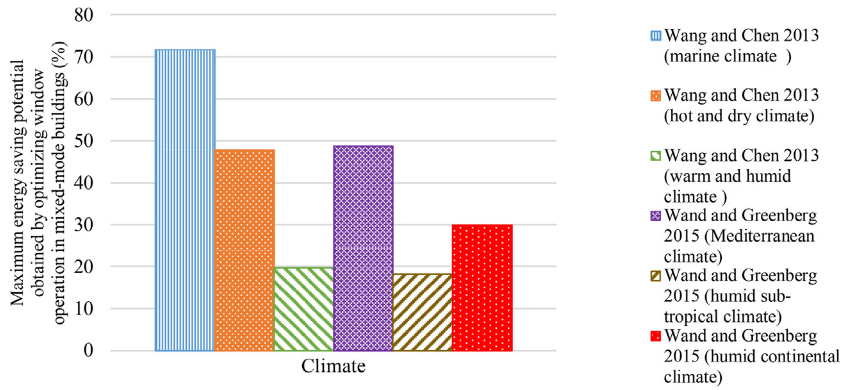

Fig. 2. Maximum energy saving potential obtained by optimizing window operation in mixed-mode buildings.

control they had over the operable windows. However, it was also observed that occupants with higher levels of control of the operable windows were much closer to the comfortable temperatures based on their preferences. The access to operating the windows themselves resulted in a higher degree of control over their own environment.

Borgeson and Brager [48] also found that occupants with access to operate the windows themselves are much closer to personally comfortable temperatures. The researchers enlisted factors that affect the occupant behavior including (1) occupancy patterns of the building; (2) different behaviors and/or clothing levels, depending on the season; and (3) the social dynamics factors which influence the window control behavior. In fact, the social dynamics factors can be classified as one of the major factors that affect the opening/closing of the operable windows. According to the researchers, anyone who has ever worked in a shared office space, knows about the varying personal criteria regarding most appropriate thermal conditions in the working area, the forms of social etiquette (polite conducts) that affect the occupant behavior regarding the opening and closing of the operable windows, and most importantly, the unspoken assumption of leadership, meaning that a "leader" person decides when to open or close the windows based on his/her personal preferences. Consequently, even when the thermal comfort inside the building may not be satisfactory for many of the occupants, the person who has the control to decide whether to open or close the windows will do it based on his/her thermal inclinations. For instance, Belleri et al. [15], conducted a study to determine the factors that mostly affect natural ventilation in buildings. These parameters included, in order of significance, the occupant behavior model, wind-speed profile, internal heat gains (electrical and lighting), envelope conductivity, and wind pressure coefficients. From the results of the study, the researchers concluded that in a shared office environment, the prediction of occupant behavior has to improve in order to be able more accurately model and predict the performance of natural ventilation in mixed-mode buildings. In a similar study, Wei et al. [49] conducted a longitudinal monitoring study to capture occupants' window operation in a mixed-mode building in Beijing, China. According to the research results, outdoor air temperature, indoor air temperature, time of the day, the presence of people, the previous state of the windows, and outside air pollution are the factors that mostly affect how occupants operate manual windows in MMV buildings. This study infers that investigating occupant window opening behavior in different locations provides valuable and critical information that can be used for later model development and building performance simulation.

3.2.2. MPC signals

An acceptable degree of thermal comfort can be achieved with the use of natural ventilation from manually operated windows in mixed-mode buildings [47]. However, in buildings where office spaces are occupied by a large number of people, it is actually hard to expect a uniform behavior of all the occupants. Past research studies suggest that users need to be better educated about their building's environmental control systems and, on the other side, the designers and managers need to understand the type of users that are going to occupy the building to provide better and adequate designs [50,39,51]. The problem is that human behavior is not always predictable with simple probabilistic functions and, therefore, it is expected that some people, in MMV buildings, will not manage their windows very actively or regularly [48]. This is one of the main reasons why in recent years, the use of signals notifying occupants when to open or close the windows has become a popular option in the mix-mode ventilation buildings [52]. Fig. 3 shows a set of representative signals interface types commonly used in MMV buildings.

These signals are controlled by model predictive control (MPC) strategies. A model predictive control is a computer control algorithm utilized to predict the future response of a system. MPC attempts to optimize the behavior of any system by computing a sequence of future manipulated variable adjustments [54]. Many studies were conducted on MPC that demonstrated their effectiveness in reducing the energy consumption while maintaining indoor thermal comfort inside the building [55–60]. However, MPC strategies in buildings are focused on low-level, local loop controls. May-Ostendorp et al. [61] explored different MPC techniques for optimizing control sequences for window operation in a mixed-mode small ventilation office building in Boulder, Colorado (semi-arid climate) through simulation using EnergyPlus software [45]. The goal was to minimize the energy consumption, energy cost, and CO_2 emissions by manipulating operable window controls and providing window opening schedules based on the requirement at specific times of the day. The results of the study showed that by using the MPC algorithm, the small office building could have the ability to save up to 40% of cooling energy through near-optimal night cooling strategies. However, results from research studies that were conducted considering actual human behavior show that occupants in MMV buildings do not always behave as expected under simulated conditions and, for that reason, energy savings may not be as noticeable as the energy savings predicted from computer simulations. This was demonstrated in a study conducted by the Center for the Built Environment at the University of California, Berkley [62,48,61,52]. During the study, an MPC algorithm was developed to notify the occupants to "open" or "close"

Fig. 3. Signal Interface Types* [53] *(top) unlabeled open/close indicator lights, (middle) labeled open/close indicator lights, (bottom) on/off lighted open signals.

the windows based on factors such as outdoor temperature, indoor temperature limits, CO_2, humidity, and wind speed. The study was intended to assess how "open" and "close" windows signals essentially affect the behavior of the users in MMV buildings. Results from the study (which included interviews with users, site visits, and surveys in 16 United States case studies) showed that signals play a minor role in user behavior. In general, signals are usually disregarded because most of the building occupants tend not to pay attention to their windows unless they are not comfortable with the thermal environment. On the other hand, in areas with a pronounced swing in seasons, where the temperature may vary throughout the day, the occupants will tend to ignore the lights if they are required to open and close the windows more than one or two times a day [41,42].

3.2.3. Automatically controlled windows

Considering the difficulty in predicting human behavior and taking into account that designers state that "if you're serious about natural ventilation, you can't leave it up to the occupants [62]", a better solution is needed in order to optimize energy savings in MMV buildings without decreasing thermal comfort of the occupants. Automatically controlled windows are now being considered the most plausible solution to deal with the uncertainty of human behaviors. Recent research has been focused mainly on the development of MPC strategies to "instruct" automated systems to function as required [63,64,65]. For instance, Tanner and Henze [66] developed a methodology to optimize building automatic controlled window openings in mixed-mode buildings incorporating the simple stochastic models of occupant presence developed by Page et al., 2008 [67]. The results building simulation models, using EnergyPlus [45], indicate that stochastic optimization leads to a more conservative performance of mixed-mode buildings, saving only half of the energy when compared with deterministic optimal controls. These results indicated that deterministic behavior of occupants overpredicts the energy saving potential of mixed-mode buildings. The results of this research implying that heuristic strategies over-estimate the saving potential of mixed-mode buildings were validated by the investigation developed by Hu and Karava [68] who presented a control-oriented modeling approach for multi-zoned buildings with mixed-mode cooling. A deterministic model-predictive control algorithm was developed using an optimization method to decide and instruct motorized windows to open or close as required. The five-month simulation study showed that mixed-mode cooling strategies reduce the energy consumption of the building by 40.7% using heuristic decisions. In contrast, using the developed predictive control strategy only 31.0% of energy consumption was reduced. The heuristic approach showed that total exceedance hours of operative temperature (a descriptive of thermal comfort [69]) are 90% higher from the desired range as compared to the predictive strategy. Furthermore, use of predictive controller resulted in 5% less total window opening hours. The research conducted by Hu and Karava [68] followed a new pattern in which not only the energy consumption was the primary design aspect of a mixed-mode building but also the differences in individual thermal comfort were considered. The results indicated that research efforts should target the development of MPC strategies taking into account the uncertainty due to the weather forecast and occupant behavior [68].

4. Mechanical cooling systems in mixed-mode buildings

The evaluation of the performance of various mechanical cooling systems used in MMV buildings is an important factor to consider during early stages of building design. Most commonly used cooling systems in MMV buildings are: (1) static cooling systems that includes panel based radiant heating and/or cooling and slab heating and/or cooling; (2) distributed air conditioning systems that include Fan Coil Units (FCUs) and Heat Pump units (HPs) and; (3) central air conditioning systems that include Constant Air Volume (CAV) and Variable Air Volume (VAV) systems (Brager et al. [5]). Various research studies have been conducted in the past two decades to compare the performance of these cooling systems using a mixed-mode strategy based on climate locations as well as building designs.

4.1. Radiant cooling systems

There exist many possible cooling strategies and/or equipment used in mixed-mode buildings. One of the most popular is hydronic radiant cooling via chilled slabs, walls, or strategically placed panels which have proven to be favorable due to their energy performance and occupant satisfaction (Borgerson, 2010 [70]). Ezzeldin et al. [71] conducted a systematic evaluation of the performance of various mixed-mode cooling strategies for office buildings with different levels of internal heat gain and using weather data from four cities that were representative of arid climates. They developed computer simulations (using the EnergyPlus software [45]) of a single prototypical office building that included high exposed thermal mass, good shading, and opening windows. In each case, satisfactory comfort conditions and minimum ventilation rates were verified. For the study, the active cooling system used as baseline scenario was the typical VAV air conditioning system only. The results of the study showed that by simply alternating the VAV system with natural ventilation, by the opening of windows, energy savings of more than 40% can be produced when compared to using only active VAV cooling. Additionally, the results showed that higher savings (56%–64%) could be achieved when night ventilation was part of the VAV mixed-mode system in the office building. During the study, the results of the investigation showed that radiant slab cooling alternated with natural ventilation is the most efficient method of MMV attaining up to 67% of energy savings as compared to office buildings using only the active VAV cooling system.

Borgeson et al. [72] developed computer simulations of the Kirsch Center at DeAnza College in Cupertino California to characterize the energy performance of the mixed-mode building operation in 16 different California state climates using the EnergyPlus software [45]. The researchers compared the energy performance of mixed-mode buildings with the radiant cooling system to mechanically ventilated buildings using only the VAV cooling system. The results of the study showed that, on average, for all the 16 different climate locations energy savings of up to 65% can be achieved with a radiant cooling system that operates only overnight as compared to buildings utilizing the VAV cooling system. Furthermore, they found that buildings modeled with Mediterranean climates using mixed-mode radiant cooling system (operating overnight and supplemented with a cooling chiller ensuring that the slab temperature set point was reached every night) outperformed in energy savings (by 8%) those buildings using only an active VAV cooling system. Borgeson and Brager [73] also concluded that for buildings modeled in the mild (Mediterranean) climates of California, natural ventilation alone is sufficient for maintaining the comfort of the occupants of the building. However, using natural ventilation only, the comfort of the occupants could not be assured in buildings simulated in hotter and dry climates. Therefore, a supplement mechanical cooling system is required. The simulation results demonstrated that buildings modeled in Mediterranean climates using a mixed-mode radiant cooling system operating overnight outperformed in energy savings (64%) buildings using VAV cooling systems (Fig. 4).

4.2. Distributed air conditioning systems using fan coil units (FCUs) and heat pump units (HPs)

Rowe [74] conducted on-site monitoring and computer simulations to study the energy consumption, occupancy, and temperature status of twenty-five offices in the Wilkinson Building at the University of Sydney, Australia. These offices used a MMV system with a supplementary reverse cycle cooling/heating system having an occupant controlled fan coil unit in each room. The simulation results showed that the energy consumption of the office spaces, using the MMV strategy, is less than a quarter (75% energy savings) when compared to the expected energy consumption of the same areas using mechanical air-conditioning only. Additionally, the on-site monitoring of the mean temperatures of occupied offices was found to have a linear association with outdoor temperatures until the outdoor daily minimum reached about 17 °C corresponding to a mean indoor temperature of about 25 °C. Finally, occupant surveys showed that perceptions of air quality and thermal comfort improved considerably since the MMV system was implemented, leading to an improved performance of the employees in these offices.

An alternative mechanical system commonly used in mixed-mode buildings is the ground source heat pump (GSHP). For example, Ji et al. [4] developed computer simulations to evaluate and compare the energy savings of an MMV building against a building using mechanical cooling from chilled ceilings cooled from ground source heat pumps located in the sub-tropical climate of south China. The building was designed as a changeover mixed-mode building with traditional mechanical cooling/heating ventilation system during hot summer and cold winter periods, respectively. According to the simulation results, the potential energy savings for MMV system as compared to traditional mechanical ventilation are about 30–35%. Another study was conducted by Ward et al. [75] that compared the energy efficiency of buildings with heat pump systems against mixed-mode buildings. During this research, an office building with no thermal mass was modeled using computer software for eight different Australian climate zones. Three different base models were developed as follows: (1) a standard case where the building was cooled using heat pumps and conditions were maintained at 22 °C and under 12 g/kg of humidity ratio; (2) a mixed-mode standard case where the building was cooled with heat pumps and fans but higher actual space temperatures were permitted and (3) a naturally ventilated case where increased air-flow rates, natural ventilation and an expanded (adaptive) comfort range from a 21 to 26 °C (perceived) were permitted. The results showed that the mixed-mode strategy in buildings with moderate climates could save up to 42% of energy during the month of January (summer). In tropical climates, the energy savings were not as pronounced as in moderate climates; however, the modeled MMV strategies could lead to a 14% of energy savings (Fig. 5).

4.3. Central air conditioning systems- constant air volume (CAV) and variable air volume (VAV) systems

Ezzeldin et al. [76] conducted a study to evaluate and critically compare the performance of office buildings located in arid climates using a mixed-mode hybrid ventilation system as compared to an active VAV system. A series of computer simulations, using the EnergyPlus software [45], were developed to model a prototypical office building. These office models were simulated under a fully air-conditioned (VAV) mode, as well as hybrid (natural ventilation and VAV) and an entirely passive mode (only natural ventilation). The computer simulation results showed that by using the mixed-mode hybrid ventilation controls, more than 60% of energy could be saved as compared to the same conventional office building designs that were air-conditioned by VAV only.

Menassa et al. [77] conducted an on-site experimental test in the Wisconsin Institute for Discovery to track the performance of MMV strategies (i.e. energy savings, thermal comfort, and IAQ) when compared to buildings in a fully air-conditioned (VAV) mode in humid continental climates. The design of the Wisconsin Institute for Discovery allows for natural ventilation to be adopted in the open zones by automatically closing the air terminal valves supplying these zones when conditions are favorable. This study found that by implementing MMV strategies, a substantial amount of energy can be saved as compared to traditional mechanical cool-

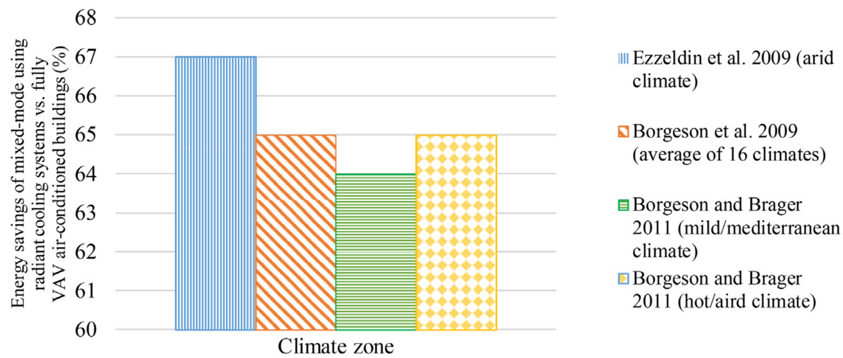

Fig. 4. Average energy savings of mixed-mode buildings using radiant cooling as compared to VAV systems.

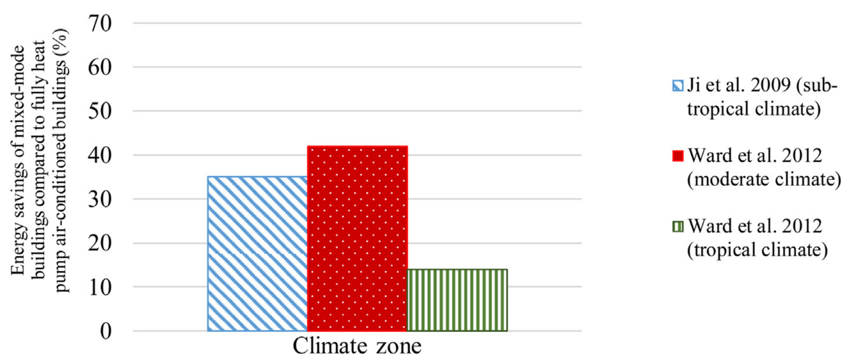

Fig. 5. Average energy savings of mixed-mode buildings as compared to mechanically cooled buildings using heat pumps.

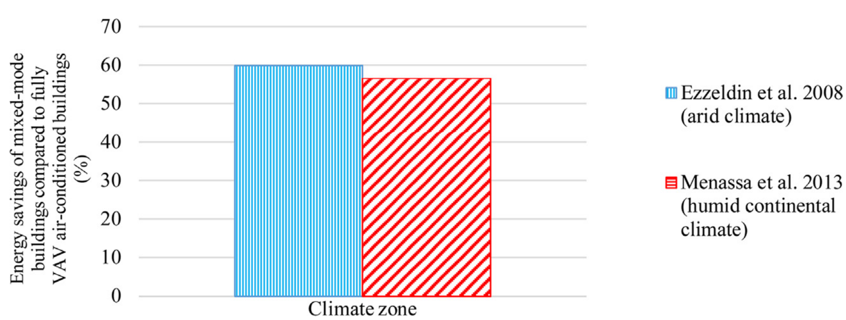

Fig. 6. Average energy savings of mixed-mode buildings compared to fully VAV mechanically cooled buildings.

ing (Fig. 6). The test results showed that by utilizing cross-flow ventilation from operating windows and opening the atria louvers in the building can provide the most energy savings (57%).

A study that compared mixed-mode buildings against buildings with traditional CAV systems was conducted by Wang and Chen [44]. They investigated the cooling energy performance of typical office buildings located in five different United States cities/climates with either a full mechanical CAV cooling system or a MMV system consisting of natural ventilation and an active CAV mechanical cooling system. The investigation was conducted through computer simulations using the EnergyPlus software [45]. The study was focused on demonstrating the impact of climate and several other important building envelope factors, such as thermal mass, insulation, and window opening area on the overall performance of mixed-mode buildings. The results showed that MMV strategies offer energy savings for the buildings in all climate zones including hot and humid climates zones (Fig. 7).

5. Limitations, challenges and recommendations for future work

Based on the comprehensive literature review conducted it can be safely concluded that a gap exists between predicted performance and actual performance of MMV buildings. The efficiency of MMV buildings depends on many factors such as building design, window operation, and individual occupant controls and the available tools are not sophisticated enough to model buildings considering all these factors simultaneously. Following are some of the limitations and challenges found through the analysis of the past and ongoing research studies related to the MMV buildings:

5.1. Limitations

Past studies have demonstrated that the presence and behavior of the occupants has a substantial impact on the thermal comfort, air quality, and reduction in the mechanical cooling energy consumption for MMV buildings. The problem is that the human

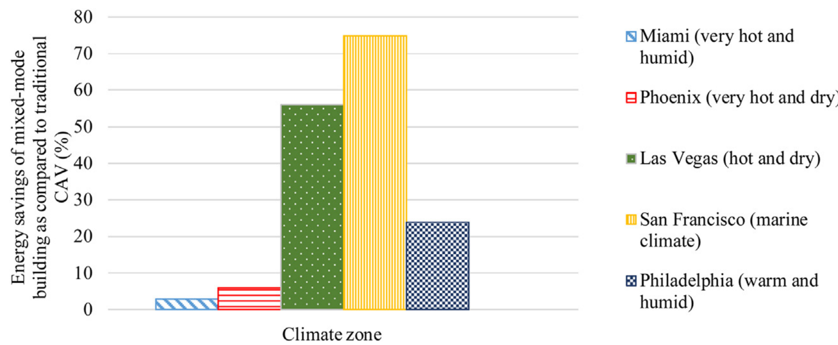

Fig. 7. Comparison of energy savings for different climates in the United States using mixed-mode CAV system.

behavior cannot be predicted (i.e. it is not deterministic) and, therefore, there is not a perfect way to model human behavior or to influence human activities in mixed-mode buildings to date. Existing simulation tools found in the literature have not reached the stage where occupant behavior, in MMV buildings, can be accurately simulated. Furthermore, it was determined that current research efforts are focusing on developing strategies to optimize natural ventilation in mixed-mode buildings through the implementation of automatically controlled windows using computer control algorithms that work based on occupancy, outside temperature and/or internal loads, instead of considering the actual occupant behavior in the buildings.

L1. Through the comprehensive literature review, it was found that less attention has been given in the past to studying the energy savings potential of MMV buildings due to building design factors.

L2. Simulation capabilities are still limited, and many assumptions or model simplifications are required in order to obtain the energy savings or performance in MMV buildings [78].

MPC is an emerging tool in the building industry, and therefore, current MPC technology uses simplified models to obtain building responses [79]. Its implementation and analysis are significantly inhibited due to the lack of commercially or publicly available software tools [80].

The current simulation strategies focus on the performance of MMV buildings based on the outside temperature, inside temperature, wind patterns, insolation, time of the day, and assume "ideal" perfect indoor conditions but do not consider the expected thermal comfort of human occupants. Studies have demonstrated that each person is different and, therefore, they have different perceptions of thermal comfort [52,55,56].

5.2. Challenges

C1. The ability to model occupant behavior in simulation software, especially for automating the window operation in MMV buildings is a primary challenge [70,81].

It is necessary to optimize control strategies for operable windows in natural and MMV buildings in order to optimize the times and duration of the opening of the windows avoiding overcooling, or loss of cooling/heating energy due to natural or MMV [43]. Furthermore, with the current problem of pollution in big cities, it is important to optimize the maximum amount of time that windows can be opened without affecting the IAQ in MMV buildings.

It is necessary that occupants of MMV buildings be aware of and educated about the fact that there are different occupant behaviors and expectations in MMV buildings. In fact, according to Masoso and Grobler [82] changing the occupants behavior in buildings has more saving potential and benefits at a lower cost as compared to implementing technological improvements. It is important to recognize and instruct people that the comfort of occupants in mixed-mode buildings is empowered with the ability of these occupants to interact with their environment. Current research [83] is focusing on engaging people with their building environment to have a user-centered approach and to increase energy savings in buildings. Some other researchers are also focusing on finding out how peer network affect the energy saving potential in buildings [84].

5.3. Future work recommendations

Numerous studies have been conducted model the occupant behavior in various types of buildings. For instance, some studies have used the statistical analyses method to model occupant presence and behavior in buildings [86]. This method uses the probability of the behavior of occupants in buildings based on outside environmental factors, indoor environment, electricity use, or time series where all somehow influence occupant behavior. Another method used in other studies in order to capture and model the occupant behavior in buildings is data mining [88,89]. This method, as the name implies, mines the energy usage data to capture and model occupant behavior patterns. The stochastic modeling approach has also been used in various studies [90–93]. Building occupants in any building behave in a random way, and therefore, stochastic modeling is an effective method to model and estimate occupancy status and energy consumption. It is recommended conduct research and to develop the capability to include occupant behavior or occupancy via any of the previously mentioned methods can enhance the potential of energy simulation tools to improve the accuracy between simulated and actual energy consumption in MMV buildings.

It is recommended to research on the sensitivity of performance of MMV buildings to wind speed and direction. It is needed to understand the critical differences between the weather station and site-specific wind data [81] in order to properly design the area of operable windows in MMV buildings. Furthermore, it is required to conduct research on how current wind pollution affects the IAQ in MMV buildings.

R1. It is recommended to develop commercial MPC technology to optimize energy savings that will lead to the confidence and credibility of savings in MMV buildings.

It is recommended to research and develop control systems that can accommodate individual occupant thermal comfort preference, and based on these preferences the control system could make consistent adjustments to meet individual needs in different zones inside an MMV building [94].

It is recommended to improve designs of MMV systems by including the collection of data from field studies (to gather actual thermal conditions, ventilation levels, indoor air quality, etc.) in real MMV buildings. Extensive publication of case studies of existing

MMV buildings can help in developing specific design and performance standards for MMV buildings [95].

6. Conclusions

In the United States, India, China and The United Kingdom an average of 35% of the total energy consumption is used by commercial office buildings. Moreover, a significant amount of this energy is used to maintain comfortable indoor environmental conditions. A comprehensive state-of-the-art literature review was conducted to study the potential use of a hybrid ventilation system in office buildings. The objective of this literature review was to learn, evaluate, and compare research studies that have been conducted in the past two decades related to MMV systems. The study of more than ninety research publications showed that the presence of occupants and their behavior have a significant impact on the thermal comfort, air quality, and energy consumption for MMV buildings. The study also observed that to date, MMV simulation tools are limited and have not reached the level where occupant behavior can be realistically simulated. Moreover, the study found that more sophisticated algorithms are needed to avoid current model simplifications for the design of mixed-mode buildings. Future research efforts should focus on improving the energy saving potential of MMV systems through the optimization of the building internal and external layout, by accounting for different wind speed and directions, and by making use of the appropriate shading, glazing, insulation, and façade designs to reach maximum utilization of natural ventilation and to minimize the use of mechanical cooling energy. Future research studies should also include the collection of sufficient data to completely characterize which of the MMV strategies and/or mechanical HVAC systems are ideal for different climatic conditions and to help improve the efficiency of these cooling systems. Lastly, it is imperative to educate building users on the expected behavior and thermal conditions of mixed-mode buildings to reach a higher level of the energy savings.

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