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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