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Impact of natural versus mechanical ventilation on simulated indoor air quality and energy consumption in offices in fourteen U.S. cities

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ABSTRACT

This study simulated the impacts of natural versus mechanical ventilation in offices on indoor concentrations of key pollutants, as well as energy usage. A typical office building was modeled in EnergyPlus in fourteen U.S. cities to assess the energy use and airflows delivered by an ideal variable air volume (VAV) system in a range of climates. Two mechanical ventilation strategies (minimum; minimum + economizer control) were modeled, as well as two analogous natural ventilation strategies, which used a fan-driven recirculation hybrid system to maintain setpoints if necessary. Outputted hourly ventilation, recirculation, and infiltration rates were used in an indoor air model with city-specific outdoor monitoring data to compute indoor concentrations of carbon monoxide, carbon dioxide, formaldehyde, nitrogen dioxide, ozone, and fine particles ($PM_{2.5}$). Natural ventilation decreased energy use, due to a wider temperature setpoint band for natural ventilation scenarios and somewhat lower fan energy use. Indoor concentrations and indoor/outdoor (I/O) ratios of all pollutants were similar for analogous strategies, except $PM_{2.5}$, which was reduced by filtration in the supply air. Median $PM_{2.5}$ I/O ratios were a factor of 1.2, 2.2, and 6.3 larger for natural versus mechanical ventilation strategies with MERV 8, 11, and 16 filters, respectively. The filtration impact was so strong that $PM_{2.5}$ I/O ratios differed little between mechanical minimum and economizing strategies, especially as filter efficiency increased. These results can be used to understand tradeoffs of energy and indoor air pollution trends of natural versus mechanical ventilation.

1. Introduction

Buildings demand large amounts of resources. For instance, they consume roughly 40% of the energy used by the U.S. and 24% by the world [1], the residential and commercial building sectors are responsible for 40% of the U.S. carbon dioxide (CO_2) emissions [2], and building occupants account for 10% of the U.S. water consumption [3]. Heating, ventilating, and air conditioning (HVAC) systems are used in buildings to maintain desired indoor conditions, and these consume two-thirds of the site energy for residential, commercial, and public buildings [4] in the developed world. Ventilation is the intentional exchange of outdoor air with the indoor air, and conditioning ventilation air to the appropriate thermal state can potentially amount to about half of building space-conditioning energy [4]. Ventilation rates may be increased or optimized [5] to enhance occupant productivity [6,7], reduce sick building syndrome [8–10] and absenteeism [10–12], and to maintain acceptable indoor air quality [13].

Standards-setting organizations such as ASHRAE or the European Committee for Standardization (CEN) prescribe minimum ventilation rates in buildings. For instance, the minimum ventilation rate in U.S. offices at default occupant densities is 8.5 L/s/person [13]. Traditionally, fans in air handling units (AHU) in HVAC systems supply ventilation air mechanically, though a newer design paradigm attempts to use natural ventilation to supply air without fans and instead by using wind-driven flows at the building façade [14]. This shift has occurred because natural ventilation can save energy by eliminating the need for fans, by sometimes supplying larger airflow rates than in mechanically ventilated spaces, and by allowing larger allowable ranges of temperature bands in which occupants are comfortable [15]. Of course, natural ventilation alone is not feasible in all climates or at all times of year. However, hybrid approaches are also possible which use a mechanical recirculation system to complement natural ventilation to meet loads or which may employ additional operational strategies such as thermal night flushing [16].

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Though standards such as ASHRAE 62.1–2013 try to safeguard indoor air quality (IAQ) with ventilation, its actual impact on IAQ is more complex. By its act of bringing in more outdoor air, ventilation has the potential to increase indoor concentrations of outdoor originating pollutants, while decreasing indoor emitted ones [17–19]. In offices, for example, important outdoor sourced pollutants can include particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) [20–23], and important indoor emitted pollutants include volatile organic compounds (VOCs) and carbon dioxide (CO_2) [18,24]. Since Americans spend ~87% of their time in buildings [25], indoor exposure to these pollutants can be a dominant route [21,26–29]. This exposure is important, as studies suggest that exposures to PM [30–36], ozone [37,38], NO_2 [39,40] and certain VOCs [40,41] are associated with increased morbidity and mortality.

There is one major distinction between the impacts of natural versus mechanical ventilation on indoor exposures. Namely, mechanically ventilated buildings have the potential to reduce indoor PM concentrations in a way naturally ventilated spaces cannot, even at high ventilation rates, since those buildings near-universally employ PM filters in the supply airstream [13], through which mechanically ventilated air passes. For instance, Quang et al. [22] demonstrated in three mechanically ventilated offices that filters were efficacious at controlling indoor concentrations of PM of outdoor origin, measuring efficiencies of 26–47% for fine and ultrafine particles. Modeling suggests the same conclusion for a variety of building types [24,42–48]. Since non-hybrid natural ventilation supplies air only through the building envelope, rather than through an AHU, the supply air cannot be filtered before it reaches the building occupants. As a result, one study predicted that locating a naturally ventilated building next to a roadway may lead to indoor PM concentrations near those of outdoors or up to ~20% higher due to the lack of filtration [49]. As such, the concentration of and exposure to indoor PM of outdoor origin may be greater in naturally versus mechanically ventilated spaces.

To greater understand this impact, as well as the impact of natural versus mechanical ventilation on indoor pollutant concentrations, this work explored the differences in indoor concentrations of PM and other important IAQ indicators within offices with mechanical versus natural ventilation, as well as energy use differences. Offices were chosen because they are a typical building type that is operationally amenable to both ventilation types. To assess the impact of these different ventilation paradigms on IAQ, we simulated the transient energy use and ventilation rates using a building energy model of a typical office in 14 U.S. cities, separately considering two natural and two mechanical ventilation strategies. Outputted building airflow rates were used with outdoor monitoring data in mass balances to predict the indoor concentrations of the indicator pollutants. These results were analyzed to allow more informed decision-making about the impacts of each ventilation type on IAQ and energy in offices.

2. Methodology

2.1. Simulation overview

Annual simulations at an hourly timescale were conducted to assess the impacts of four ventilation strategies—two mechanical and two natural—on energy consumption and IAQ in a typical office in 14 representative locations, using their typical meteorological years (TMY) and recent outdoor pollution data. Then, those annual hourly transient results from simulations in the 14 cities were pooled and analyzed as one combined dataset, and outcome trends as functions of influential variables were explored. For the pooled analysis, the pollutant indoor/outdoor (I/O) ratio was our primary parameter of judgment of ventilation strategy impacts, since it is independent of city-to-city pollution variation, though summary statistics of absolute concentration distributions in each city are provided as well. The simulation framework is generally introduced in this sub-section, and specific details are given afterward.

A complete simulation herein consisted of a coupled building energy model using U.S. Department of Energy (DOE) EnergyPlus Energy Simulation Software and an indoor concentration model using standard, well-mixed mass balances formulated for offices. EnergyPlus is a validated, physics-based, research-grade energy analysis and thermal load modeling program [50,51] that, for a particular building and climate, calculates the year-long transient heating and cooling necessary to maintain thermal and ventilation setpoints, as well as operational states of the HVAC equipment. First, we used EnergyPlus to model a standard office building with the four ventilation strategies to quantify hourly energy usage and air exchange rates (AER). Then, along with hourly ambient pollution data from 2013 or prior [52], those AERs were used in mass balances with other typical parameters to predict the yearlong, hourly indoor concentrations and I/O ratios of pollutants of interest (e.g., as in Rackes and Waring [18,24]).

For the modeled office in each city, two analogous mechanical and two natural ventilation strategies were simulated, which were chosen based on adherence to current standards [13] or characteristic operational regimes, as well as to facilitate comparisons. The two modeled mechanical ventilation strategies are frequently implemented in real buildings, and they were:

- ***Mech_min***: *mechanical ventilation minimum* strategy, for which the ventilation rate was constant at the minimum office rate (2.5 L/s/person plus 0.3 L/s/m^2) according to ASHRAE Standard 62.1–2013 [13].
- ***Mech_econ***: *mechanical ventilation economizing* strategy, for which more outdoor air is introduced into the indoor space during times when it is thermodynamically favorable (i.e., free cooling), but the ASHRAE Standard 62.1–2013 minimum rate is the operational state otherwise.

The two natural ventilation cases were chosen to mimic the mechanical ventilation cases such that they were tuned to provide nearly the same amount of ventilation air on average, but by using wind-driven flow through the envelope rather than through the AHU. The natural ventilation strategies were:

- ***Nat_min***: *natural ventilation minimum* strategy, which had rates similar to *Mech_min*.
- ***Nat_econ***: *natural ventilation economizing* strategy, which had rates similar to *Mech_econ*.

Strictly achieving natural ventilation flows at this level of control is currently operationally infeasible in buildings. However, the strategies modeled herein were designed to facilitate direct comparison of the energy consumption and indoor air concentrations resulting from the ideal implementation of these mechanical and natural ventilation analogues that exist at the ventilation airflow boundaries of low, minimum flow (*Mech_min* and *Nat_min*) and high, economizing flow (*Mech_econ* and *Nat_econ*). Of course, natural ventilation is not ideal in every climate from a thermal perspective and sometimes may not be capable of meeting the thermal loads. During these times, a hybrid system was automatically employed in which a recirculating air system was used to provide conditioning to help meet the thermal loads. Though the primary purpose of this hybrid system was to condition the