VENTILATION, ENERGY AND IAQ IMPACTS OF MECHANICAL VENTILATION IN A US DWELLING

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ABSTRACT

Based on concerns about indoor air quality and trends towards tighter envelope construction, there has been increasing interest in mechanical ventilation of residential buildings in the United States. This paper reports on a simulation study of indoor air quality, ventilation and energy impacts of several mechanical ventilation approaches in a single-family residential building. The study focuses on a two-story house in the northwestern United States and employs the multizone airflow and contaminant dispersal model CONTAM96. The contaminants studied include carbon monoxide, carbon dioxide, nitrogen dioxide, water vapor, fine particles, and a generic volatile organic compound. One-year simulations were performed for a base case of envelope infiltration, passive inlet vents with intermittent mechanical exhaust, outdoor intake to the forced-air system return balanced by mechanical exhaust, and continuous exhaust. Results discussed include whole building air change rates, energy consumption and contaminant concentrations.

INTRODUCTION

While existing data are limited, there appears to be a trend towards tighter envelope construction in single-family buildings in the U.S. This trend, along with energy-efficient construction programs, has led to the realization that mechanical ventilation may be needed in some dwellings. However, questions exist about the effectiveness of these systems in terms of indoor contaminant control, ventilation rates provided, air distribution, and energy impacts. This paper reports on a study in which computer simulations were used to examine these issues in a house representing recent energy-efficient construction in the Pacific Northwest region of the U.S. Reference [1] contains a detailed description of the study and the results; this paper presents only a summary.

The simulations in this study employed the multizone airflow and contaminant transport model CONTAM96 [2], in which a building is represented as a system of interconnected zones. Airflow paths between zones are specified along with other information relevant to airflow such as ventilation system parameters, outdoor weather, and wind pressure coefficients. CONTAM96 then calculates airflow rates between the zones based on a simultaneous mass balance of air for all the zones. In addition, given information on contaminant sources and removal mechanisms and on outdoor concentrations, CONTAM96 calculates contaminant concentrations in the zones. The program also calculates occupant exposures to contaminants based on occupancy schedules input by the user.

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SIMULATION APPROACH

The simulations in this study cover an entire year for Spokane, Washington and were performed a month at a time to allow the use of monthly schedules of forced-air system on-time and to extract monthly summaries of the model outputs. Six cases were analyzed:

Case #1: All fans off; all interior doors open.

Case #2: Forced-air fan, exhaust fans and interior doors on schedules.

Case #3: Passive inlet vents open with intermittent mechanical exhaust.

Case #4: Intake duct on forced-air fan with intermittent mechanical exhaust.

Case #5: Reduced duct leakage and continuous exhaust.

Case #6: Constant air change rate of 0.35 h^{-1}.

Case #1 was analyzed to assess ventilation rates due to envelope leakage alone. Contaminant concentrations were not calculated for this case. Case #6 is an idealized case in which the house has a constant air change rate of 0.35 h^{-1} for every hour of the year, always complying with the outdoor air requirement in ASHRAE Standard 62-1989 [3].

DESCRIPTION OF HOUSE MODEL

The house represents recent residential construction in the northwestern U.S., where there have been aggressive energy efficient construction programs. It is a fictitious two-story house, with a crawl space, attached garage and attic. The first floor of the house has seven zones: kitchen, dining room, living room, bath, two closets and an entry. Figure 1 presents a floor plan of the first floor, as represented within CONTAM96, showing icons that represent airflow paths, contaminant sources and ventilation system elements. The second floor has eight zones: a master bedroom, three smaller bedrooms, three baths, a closet and hallway. Reference [1] describes the layout of the house in detail. The airflow characteristics of the house, that is, the location and magnitude of the various air leakage paths in the exterior walls and interior partitions are based on a similar house studied in a previous modeling effort [4] and are also described in reference [1].

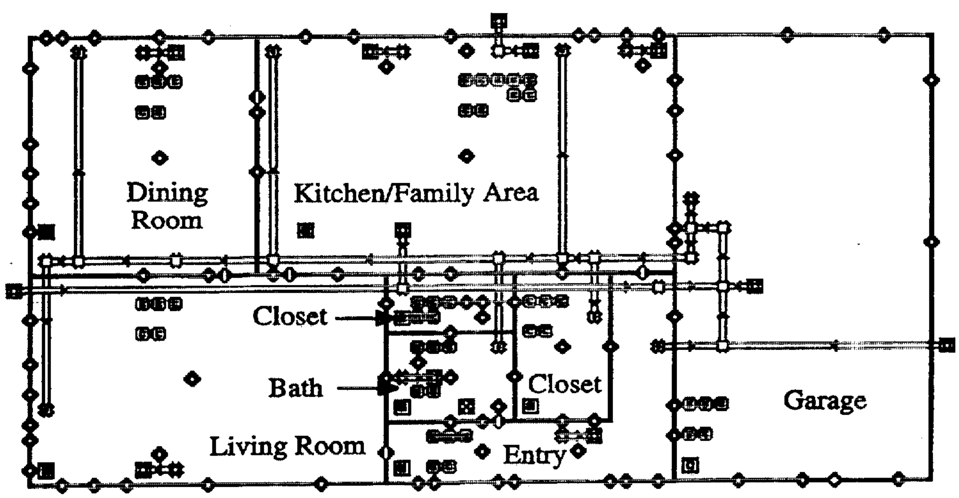

Figure 1 CONTAM96 Representation of the First Floor

Ventilation System

The house model has a forced-air heating and cooling system and local exhaust systems in the kitchen area and bathrooms. The air handler is located in the attached garage, as is common in this region of the U.S. The supply ductwork serving the first floor runs through the crawl space, while the supply ductwork serving the second floor runs in between the first and second floors. A single return serves each floor, with the return ductwork running through the attic. The forced-air fan is simulated to operate for a constant fraction of on-time for each hour. This fraction varies for each month of the year, and is based on the mean outdoor temperature for the month. In order to account for the impacts of duct leakage, openings in the duct system are included on the return side of the air handler in the garage, in the attic return duct, in the return duct in the first floor ceiling, and in the crawl space supply duct.

The study focused on three approaches to mechanical ventilation: passive inlets and intermittent mechanical exhaust (Case #3); an outdoor air intake duct on the forced-air system return with intermittent exhaust (Case #4); and constant mechanical exhaust (Case #5). For Case #3, vents with an effective leakage area of 15 cm^2 at 4 Pa were placed in each of the three small bedrooms and the dining room. In addition, two were placed in the master bedroom and three in the living room. These vents were always open. An exhaust fan in the master bathroom operated 8-h per day with a capacity of 44 L/s. This airflow rate corresponds to about 0.35 h^{-1}, which is the outdoor air requirement for residential buildings in ASHRAE Standard 62-1989 [3].

For the outdoor air intake system (Case #5), the intake duct was modeled such that roughly 43 L/s of outdoor air was drawn into the system when the forced-air fan operated. This duct is open on an 8-h schedule each day, at which time the forced-air fan and the 44 L/s exhaust fan in the master bathroom operated, resulting in a balanced ventilation system. The intake duct is also open when the forced-air fan operates based on space conditioning needs. At these other times, the master bathroom exhaust fan does not operate. The last ventilation approach studied involves an exhaust fan that operates continuously in the master bathroom. The exhaust fan capacity in Case #5 is 32 L/s, which is sized to yield 0.35 h^{-1} in combination with envelope infiltration. In addition, the air distribution system duct leakage is reduced to 10% of its original value to reduce overventilation when the forced-air fan is operating.

Occupants

To account for occupant-generated contaminants and to determine the exposure of building occupants to indoor contaminants, a family of five is assumed to occupy this house. These occupants are based on other simulation studies and expectations for a modern U.S. family. However, no attempt was made to base this family on an analysis of census data, residential occupancy patterns or other information. The five family members are as follows: an adult male working full-time, an adult female working part-time, a 16 year-old child, a 13-year old child, and a 10-year old child. Each individual is associated with an occupancy schedule that specifies the time spent in each room of the house, as well as out of the house. Based on these schedules, CONTAM96 accounts for the contaminants generated by each individual and the contaminant concentrations to which they are exposed.

Contaminants

Six contaminants are considered in the simulations: carbon dioxide, carbon monoxide, nitrogen dioxide, water vapor, fine particles (diameters < 2.5 μm), and volatile organic compounds. The details of the contaminant modeling, including the emission rates, are contained in reference [1]. The sources of these contaminants include occupant respiration and other activities, gas cooking, building materials and outdoor air. Surface deposition of NO_2 and fine particles is accounted for using a first order loss coefficient. VOCs are emitted by a generic source in each room, scaled by floor area. The emission rate in each room is 0.21 mg/s per m^2 of floor area. A single VOC is simulated and is intended to account for the combined emissions of VOCs from building materials and furnishings. While indoor VOCs include a broad class of compounds with varied characteristics and health impacts, the inclusion of multiple compounds would have greatly complicated the study. The effects of absorption and desorption of VOCs on interior surfaces are accounted for using a boundary layer diffusion controlled (BLDC) model with a linear adsorption isotherm [1, 5]. The effects of water vapor absorption and desorption by building materials are addressed using a model developed at CSTB [6]. Water vapor removal by the air conditioning equipment was approximated using the filter element of CONTAM96. The filter efficiency of 17% is based on an idealized cooling coil, which is assumed to operate only during the summer and only when the forced-air system is on.

RESULTS

The results of this study are discussed in detail in reference [1]. The airflow-related results include building airtightness, internal airflow patterns, ventilation rates, air distribution, and energy consumption. Contaminant concentrations and occupant exposure were also determined. The contaminant results are presented as monthly mean concentrations that are averaged over zones and time frames specific to each contaminant. For example, VOCs are analyzed as hourly averages over the occupiable zones of the house, e.g., excluding closets. Hourly values of relative humidity are averaged over all zones of the house. CO_2 is averaged over the four bedrooms, and the maximum hourly value for each day is analyzed for each month. A brief summary of these results is presented below in Figures 1 and 2.

Figure 1 contains the mean air change rate, the percentage of hours below 0.35 h^{-1} and above 0.70 h^{-1}, and the heating, cooling and fan energy for the six cases. Cases #1 (envelope infiltration only) and #2 (infiltration plus exhaust fan operation and duct leakage) both have many hours of under-ventilation relative to the residential requirement in ASHRAE Standard 62-1989 of 0.35 h^{-1} [3]. This demonstrates the inability of infiltration to provide "adequate" ventilation for this climate and level of airtightness. Cases #3 and #4, inlet vents and forced-air intake, are often "overventilated" as seen by the percentage of hours above 0.70 h^{-1}, mostly due to duct leakage. The overventilation is particularly significant for Case #4, where the forced-air fan brings outdoor air into the building. However, the percentages of hours during the year when the air change rate is below 0.35 h^{-1} for these two cases are still significant. Case #5 (continuous exhaust and reduced duct leakage) is also slightly "underventilated" due to the sizing of the continuous exhaust fan. This could have been "remedied" with a slightly higher fan capacity. Figure 1 shows that heating and cooling energy consumption is roughly proportional to the mean air change rate. An energy penalty due to forced-air fan operation is seen for Case #4. The heating and cooling energy consumption of Case #5 is closest to Case #6 (constant air change rate of 0.35 h^{-1}), showing good "control" of loads for this case.

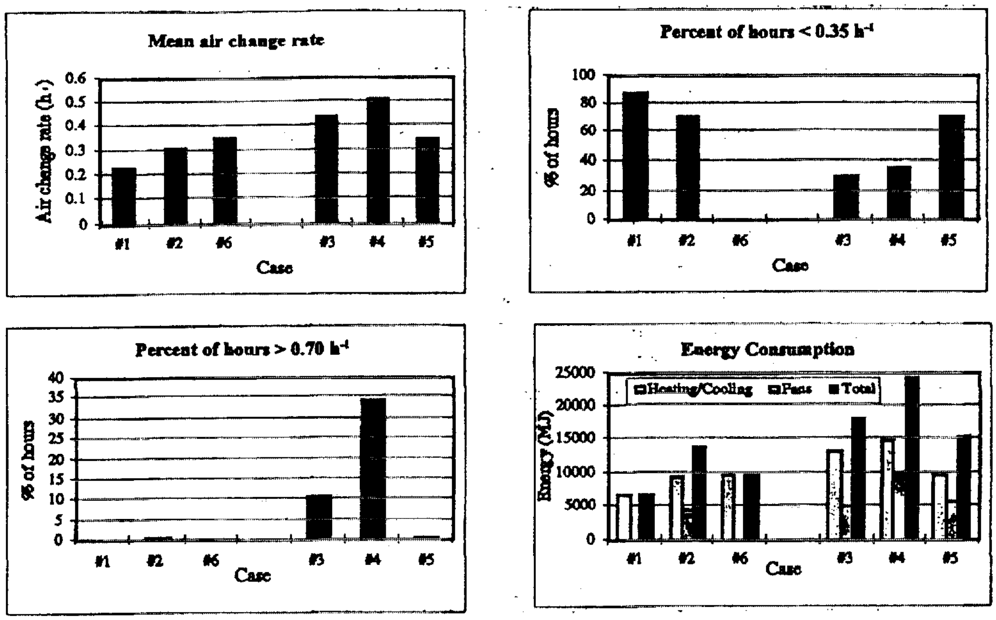

Figure 1 Summary of Air Change Rate and Energy Consumption Results

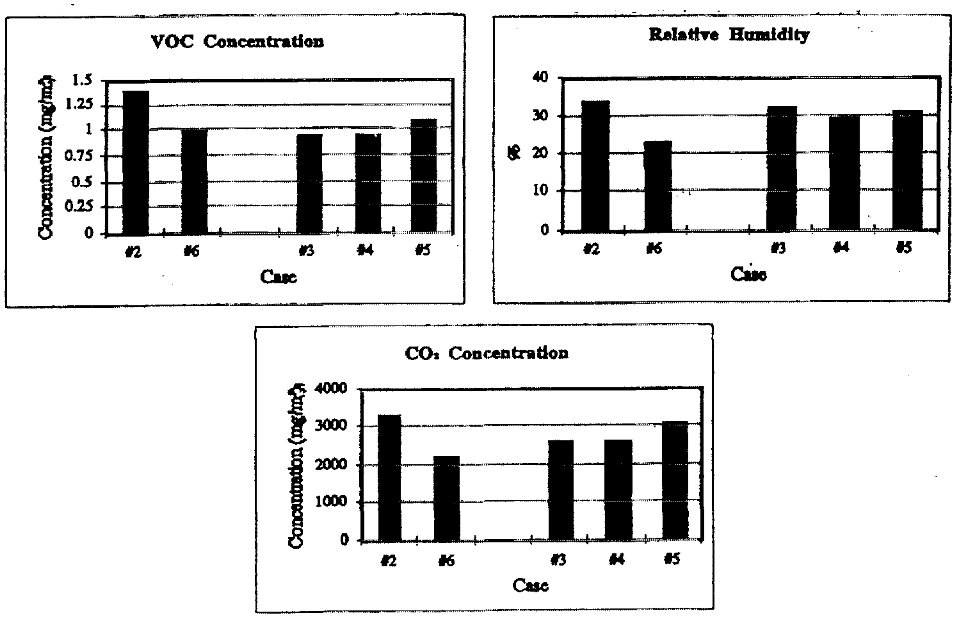

Figure 2 Summary of Contaminant Concentration Results

Figure 2 summarizes some of the contaminant concentration results, presenting the annual average VOC, relative humidity and CO_2 levels for the six cases analyzed. The concentrations for contaminants with constant outdoor levels, VOC and CO_2, are roughly proportional to the outdoor air change rate. Relative humidity is also impacted by internal storage and variations in the outdoor humidity. In considering these results, absolute concentrations for a given case are of less interest than relative concentrations between cases because the absolute concentrations depend on the specific input values used in the simulations, and many of these are not known particularly well.

DISCUSSION

These simulations show the impacts on ventilation, energy, contaminant concentration and occupant exposure of selected mechanical ventilation approaches in a residential building. The results show that envelope leakage, even in a relatively tight house, can result in overventilation (relative to the residential ventilation requirement in ASHRAE Standard 62-1989) during severe weather. This is particularly true in houses with significant levels of duct leakage. However, the same house can be underventilated during mild weather conditions. Mechanical ventilation systems can increase the air change rate during mild weather, thereby reducing contaminant concentrations and occupant exposure, but the issue of overventilation remains. In order to deal with overventilation, a tighter building envelope and reduced duct leakage appear to be required. In terms of the different ventilation approaches that were investigated, the reductions in contaminant concentration and exposure are to the first order related to the increase in air change rate. Deviations in that relationship do exist for contaminants with emissions that are episodic or localized, such as those associated with cooking. The relationship between concentration and air change rate is more complicated for contaminants, such as water vapor, where the outdoor concentration varies with time.

ACKNOWLEDGEMENTS

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