IMPACT OF VENTILATION MODIFICATIONS ON INDOOR AIR QUALITY CHARACTERISTICS AT AN ELEMENTARY SCHOOL

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ABSTRACT

Mechanical ventilation systems, designed to meet ASHRAE's Standard 62-1989 and to modify building pressures, were installed in two New Mexico elementary schools to reduce elevated levels of indoor radon, carbon dioxide, and airborne particles. Although the systems did not meet design conditions for outdoor air delivery, ventilation rates were increased by factors of 2 to 4 over pre-existing natural ventilation rates, and levels of indoor air pollutants were significantly reduced. Operation of the ventilation systems reduced radon levels to less than 70 Bq m^{-3} and average mass (PM_{10}) and count (particles greater than 0.5 μm) concentrations of airborne particles approximately 10 to 70%. Average pre-existing indoor concentrations of carbon dioxide (CO_2) were reduced from 20 to 60% by the additional ventilation, but not always below ASHRAE's guideline of 1000 ppm. Estimates for the additional energy cost to operate the ventilation systems ranged from \$700 to \$1300 per year.

INTRODUCTION

Because classrooms are some of the most densely occupied indoor spaces, proper control of this environment is difficult. Recent studies of schools across the U.S. have found poor temperature and humidity control, elevated concentrations of indoor air pollutants, insufficient ventilation, and inadequate repair and maintenance programs (1,2). Pollutant concentrations measured in these schools can create an unsatisfactory learning environment, and in some cases pose a serious health risk to both students and staff. This paper reports on a study to examine the impacts of ventilation modifications on the concentrations of indoor CO_2, airborne particles, and radon in three elementary school buildings. These modifications were made in two of the buildings to control elevated indoor radon levels. The third building was an unmodified control. More detailed information is reported by Turk *et al.* (3,4).

METHODS

Site description

The school buildings (#1- control, #2, #3), housing primarily classrooms (grades kindergarten through 6), are located in a residential area of Santa Fe, New Mexico. The area is at an elevation of about 2134 m, with a semi-arid climate and approximately 3400 heating degree-days (base 18.3 °C) per year. The campus is primarily asphalt-covered with nearby dirt/grass playgrounds, and dirt streets bordering on two sides. Typical classroom hours are from 8:00 AM until 3:00 PM, Monday through Friday, with a morning and afternoon recess and lunch from 11:30 am until 12:30 PM. Custodial activities occur from approximately 3:30 PM to 6:00 PM. Tobacco smoking is not permitted in any of the buildings. The 50 to 60 year old buildings are single-story masonry structures with air-tight, accessible crawlspaces and small basement/mechanical rooms. All rooms and hallways have carpeted floors. Prior to the radon mitigation, the buildings were all naturally ventilated with operable windows.

Ventilation systems

Because funding was available to remove asbestos-containing material (ACM) from only one of the three crawlspaces, different radon mitigation techniques appropriate for buildings with and without existing asbestos problems were installed. A heat recovery ventilator (HRV) was installed in building #2 (with ACM removed), with the exhaust fan depressurizing the crawlspace and the supply fan pressurizing the classrooms with outdoor air tempered by the heat exchanger core. The HRV was configured to allow independent operation of the supply and exhaust fans. In building #3, a rooftop, supply-only, ventilation system was installed. The system pressurizes the occupied space to inhibit radon from entering from the crawlspace, without disturbing the ACM in the crawlspace.

Medium efficiency (30 to 40% atmospheric dust spot) pleated air filters were installed in the outdoor air stream of the systems in both buildings. Modifications were made to ensure thermal comfort of the occupants in the rooms receiving increased ventilation air. The new ventilation systems for both buildings were designed to furnish outdoor air at a rate of 8 l s^{-1} (15 cfm) per occupant, as recommended by the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) in standard 62-1989.

Time clocks control the systems, turning them on at approximately 6:00 AM and off at approximately 6:00 PM, Monday through Friday. The effects of various modes of system operation (i.e. different combinations of supply fan on/off, exhaust fan on/off and windows open/closed) were examined, along with baseline periods (all systems off), for at least two days during a five-week testing period. The two-day periods were scheduled for the same days of each week (Wednesday and Thursday) so that (a) classroom activities would be more similar from one period to the next, and (b) indoor environmental conditions were more likely to have stabilized after the weekend. During baseline conditions, the windows in each building were intentionally kept open to minimize the occupant's radon exposure. Longer-term (approximately one year) monitoring of radon, CO_2, and differential pressures was conducted while systems were cycled.

Measurement protocols

Outdoor air ventilation rates were measured in the mornings (during occupancy) by the tracer gas decay technique (ASTM 1993) using sulfur hexafluoride (SF_6) as the tracer gas. Pure SF_6 was manually injected and mixed in all of the rooms in each building to achieve starting concentrations of about one part per million of SF_6. Tracer concentrations in air samples from two classrooms in each of buildings #1 and #2 were measured semi-continuously every eight minutes using a Brüel & Kjær model 1302 multi-gas analyzer with a detection limit of 10 ppb. Sampling continued for approximately 3.5 hours, or until the concentrations had fallen to the detection limit of the gas analyzer, whichever came first. In addition to the four room measurements, whole-building average ventilation rates were determined by taking walkthrough, one-liter bag samples from all occupied spaces at 20-minute intervals.

Carbon dioxide concentrations were continuously monitored outdoors and in two classrooms of each building using Gaztech Ventostat passive non-dispersive infrared monitors. The voltage signals from these monitors, along with wind speed and direction, and outdoor, room, and crawlspace temperatures, were scanned every 10 seconds by Campbell Scientific model 21X data loggers located in each building and stored as 30-minute averages.

Airborne particles were measured outdoors and in one classroom of each building. Gravimetric measurements of PM_{10} (suspended particles with aerodynamic diameter ≤ 10 microns) were made using particle impactors sampling air at a flow rate of 0.167 l s^{-1} (10 l min^{-1}). Sampling periods were usually from 7:45 AM until after the end of class each day, approximately 3:30 PM. Particle count concentrations were compiled at the same locations as the PM_{10} samples using portable, laser diode-based devices (Climet model 4100) with a flow rate of 0.0467 l s^{-1} (2.8 l min^{-1}) that counted particles in two ranges (greater than 0.5 μm, and greater than 5.0 μm) over 10-minute periods.

Indoor and crawlspace radon levels were measured with continuous radon monitors (Femto-tech model R-210F and Pylon AB5). Differential pressures (referenced to the classrooms) were measured between the classroom and crawlspace, and between the classroom and outdoors at five of the study rooms using variable capacitance transducers (Setra model 264).

RESULTS

A summary of ventilation rates, and concentrations of CO_2, airborne particles and radon for several configurations of the ventilation systems is presented in Figure 1. For building #2, the configurations are abbreviated as -- CRAWL DEPRESS: depressurization of the crawlspace by operation of only the HRV exhaust fan, SUPPLY VENT: ventilation of the occupied space through pressurization (windows and doors closed) or with windows and doors open by operation of only the HRV supply fan, FULL MITIGATION: both crawlspace depressurization and occupied space ventilation by operating both HRV fans; while for building #3 -- SUPPLY VENT: ventilation of the occupied space with windows and doors open, and SUPPLY PRESSURE: ventilation of the occupied space through pressurization (windows and doors closed).

Average ventilation rates were increased less than 30% during crawlspace depressurization, while supply ventilation caused average increases of up to a factor of 2.5 and increases of up to a factor of four in individual rooms. As seen in the figure, the dis-aggregated data for building #3 indicate there was little difference in ventilation rates with the windows and doors open versus closed (space pressurized).

With maximum outdoor air ventilation, daily average CO_2 levels were usually, but not always, below the recommendation of ASHRAE standard 62-1989 (1000 ppm), and frequently exceeded the recommendation at some time during the school day. Without mechanical ventilation, indoor average concentrations were often above 2000 ppm, while 30-minute maximum concentrations reached 4500 ppm.

The additional outdoor ventilation air caused reductions in indoor PM_{10} concentrations of

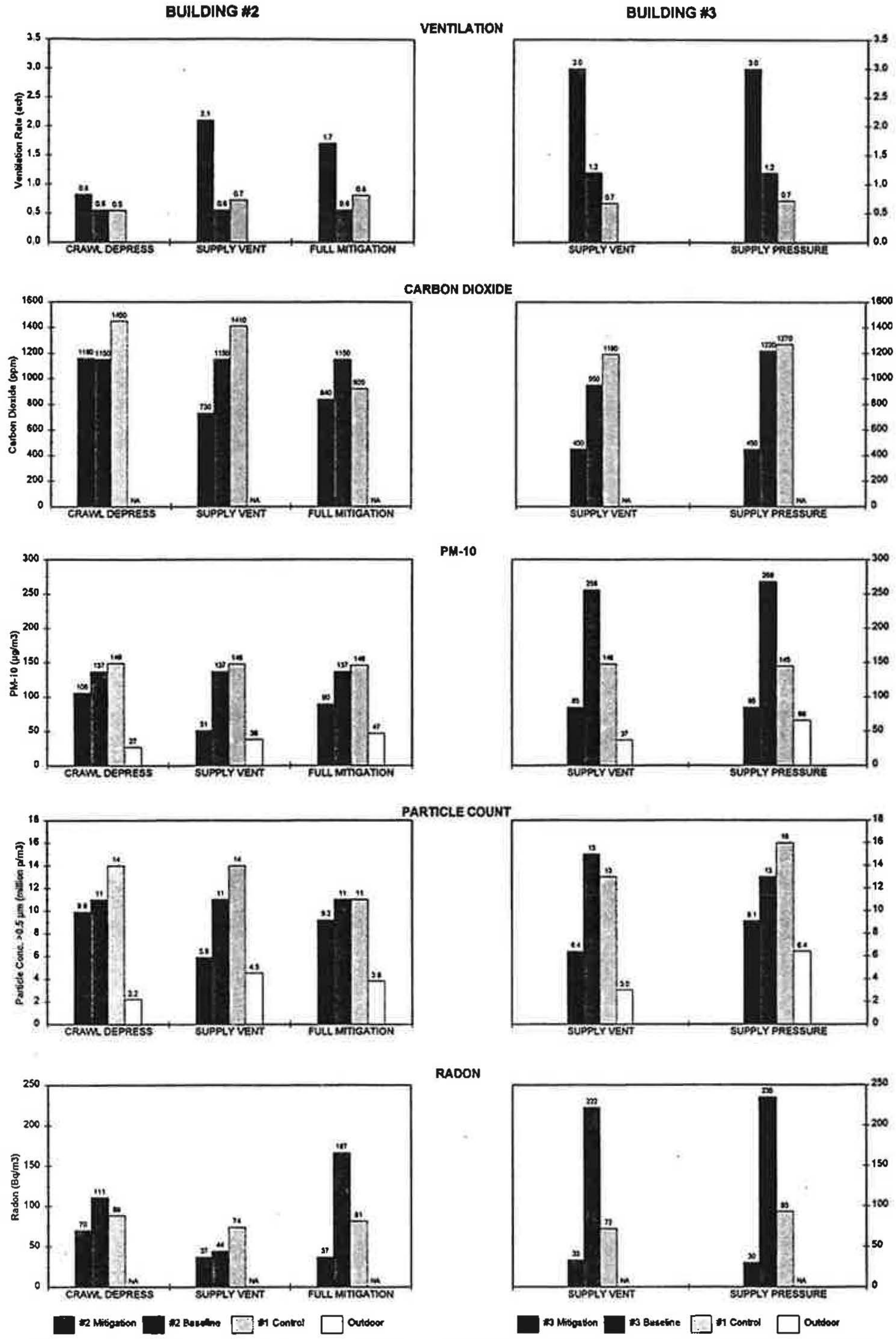

Figure 1 Summary of indoor pollutant and ventilation measurements during various operating configurations in buildings #2 and #3. Data generally represent two-day averages during occupied hours (except for radon) for selected classrooms in each building, and compare mitigation with corresponding baseline periods in the same building and in the control building (#1).

approximately 20 to 70%, and in particle count concentrations (for particles greater than 0.5 μm) of approximately 10 to 60%. Measured PM_{10} concentrations in one classroom in building #3 were very high on four separate days (359, 246, 241, and 177 $\mu g\ m^{-3}$) during baseline conditions. Indoor particle concentrations were always higher than outdoors, except during unoccupied periods when indoor count concentrations (ranging from 1.5×10^6 to 4.2×10^6 p m^{-3}) were similar to those in the outdoor air.

All configurations of the ventilation systems were effective at mitigating indoor radon levels below the U.S. EPA's action level of 150 Bq m^{-3} (4 pCi l^{-1}). Measurements made prior to the study with two-day charcoal canisters found indoor levels often exceeded 370 Bq m^{-3}, and approached 1480 Bq m^{-3} in two classrooms. Differential pressures between classrooms and crawlspaces typically increased approximately 13 Pa due to crawlspace depressurization, 2 to 7 Pa for supply ventilation, and 6 to 13 Pa for supply pressurization.

Total installation costs ranged from approximately $32,000 (US) for the rooftop system at building #3 to $61,000 for the HRV system at building #2. A score keeping energy analysis program (PRISM) was used with meter readings and outdoor temperature data to estimate that additional annual energy costs ranged from approximately $700 (building #3) to $1300 (building #2 - full HRV operation). The overall average efficiency of the HRV (October through May) was calculated to be 0.45, which is estimated to have saved approximately $400 per year in natural gas costs as compared to a ventilation system without heat recovery.

DISCUSSION

This study has demonstrated that the levels of several common indoor air pollutants can be dramatically reduced when additional outdoor air is provided to the occupied spaces by mechanical ventilation systems. This assumes that the concentrations of the pollutants in the outdoor air are less than those indoors. For the school buildings involved in this study, typical infiltration rates with windows open ranged from about 0.4 to 1.2 ach. Despite large increases in ventilation rates, tracer gas decay tests showed that none of the rooms or buildings consistently achieved the design objective of providing ASHRAE-recommended quantities of outdoor air. Under maximum conditions of mechanical ventilation, delivered outdoor air flows ranged from approximately 3.3 to 8.0 l s^{-1} (7 to 17 cfm) per occupant. Flow measurements from supply diffusers confirmed the ventilation deficit, while flow measurements in the main supply ducts indicated sufficient air flow to easily meet or exceed the guidelines. Presumably, leaks in the air distribution system or poor mixing of the supplied outdoor air into the occupied zone resulted in the discrepancy. From the limited data in this study, opening or closing windows and doors appeared to have no effect on the overall ventilation rates during operation of the systems.

The increased outdoor air ventilation reduced concentrations of all indoor pollutants that were measured. The response of indoor CO_2 concentrations to the change in ventilation rates was less than that predicted by a simple mass balance relationship, however, occupancy rates were not constant among the test periods.

The high PM_{10} concentrations measured in several classrooms during baseline conditions clearly exceed most commonly recognized guidelines for annual average PM_{10} concentrations (50 $\mu g\ m^{-3}$), as did concentrations in several classrooms during maximum outdoor air ventilation. Some measurements even exceeded recommendations for 24-hour exposures (150 µg m^{-3} -- U.S. EPA, NAAQS 1995). The ratio of count concentrations for larger airborne particles (greater than 5.0 µm) to the smaller particles tended to decrease during operation of the mechanical ventilation equipment, suggesting that the ventilation systems are comparatively more effective at removing larger indoor particles through impaction on the filter media or air distribution equipment. Comparison of occupancy patterns with time series data for CO_2, and particle count concentrations indicate that source generation from occupant activities is the dominant factor regulating indoor particle levels. Occupant activities also appear to preferentially increase the number of larger airborne particles.

Installation costs for ventilation systems like those employed in this study may prove to be a barrier for widespread implementation by many school districts, while the increase in energy costs may also be a deterrent. However, the improvement in temperature control and the quality of the educational environment may justify the expenses.

Failures to meet guidelines and recommendations for amounts of outdoor ventilation air and concentrations of indoor pollutants may be linked to difficulties inherent in designing ventilation systems suitable for older, existing buildings, and in the proper installation and long-term repair and maintenance of the system and its components. Without a long-term commitment to training programs and good system operations, ventilation rates will begin to diminish and indoor pollutant levels will rise again.

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