Indoor Air Quality of an Energy-Efficient, Healthy House with Mechanically Induced Fresh Air

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ABSTRACT

Issues associated with indoor air quality (IAQ) and its impact on occupant health have prompted research into the design and construction of "healthy houses." Most of the houses constructed have been "upscale housing." An affordable, energy-efficient, healthy house was built at Tuskegee University with features that improve IAQ, reduce energy consumption, and do not increase the cost of the house beyond the means of the targeted homeowners. Tests were conducted on the "healthiness" of the house using a filtered fresh air ventilation system in the heating, cooling, and swing seasons. Initial tests of the Tuskegee healthy house do indicate that meeting the sometimes competing priorities of affordability, energy efficiency, and IAQ will require a more balanced combination of system operation than simply keeping the ventilation turned on. Future tests of the house will help to find a balance that best optimizes the combination of affordability, energy efficiency, and IAQ.

INTRODUCTION

According to the Environmental Protection Agency (EPA), the majority of people in the U.S. spend 90% of their time indoors, and 65% of that time is spent at home (EPA 1995). Issues associated with indoor air quality (IAQ) and its impact on occupant health have prompted research into the design and construction of "healthy houses." In a report to Congress in 1991, the EPA reported that indoor pollution levels can be from 2 to 5 times (and occasionally 100 times) higher than pollution levels found outdoors (EPA 1991). The EPA considers indoor pollution among the top five environmental risks to public health and has estimated that it costs $2 billion in medical costs and lost productivity every year (EPA 1995). A challenge facing the housing industry is to design and build "healthy homes" that address these IAQ issues.

Designs and standards are being developed that could result in improved IAQ characteristics for homes. Because healthy houses typically require the introduction of costly systems or features, most of the work to date has focused on "upscale" and "high-end" housing. However, significant numbers of low-cost and low-income housing residents (and especially children) are believed to have experienced health problems that are associated with or aggravated by IAQ deficiencies. How can a healthy house also be achieved for low-income homeowners? Is it possible to design, construct, and maintain a low-cost house that is free of mold, mildew, dust mites, and other chemical pollutants that commonly occur in much of today's housing?

The sources of pollutants that impact IAQ can be classified into three main categories: materials, inhabitants' activities and lifestyles, and outdoor pollutants. Materials include those used in construction as well as furnishings. Inhabitants' activities and lifestyles include metabolic activity that results in reduction of oxygen and the increase of carbon dioxide (CO_2) levels. Outdoor pollutants include pollen, dust in the atmosphere, and airborne industrial chemicals. Outdoor pollutants are introduced into the home through windows, doors, envelope infiltration, or the ventilation system.

Over the last two decades, design and construction of energy-efficient housing has been on the rise. An important design parameter of an energy-efficient envelope is its airtightness with minimal infiltration/exfiltration to reduce energy losses. A tight envelope can aggravate potential IAQ problems. The Occupational Safety & Health Administration (OSHA) has raised concerns about increased buildup of

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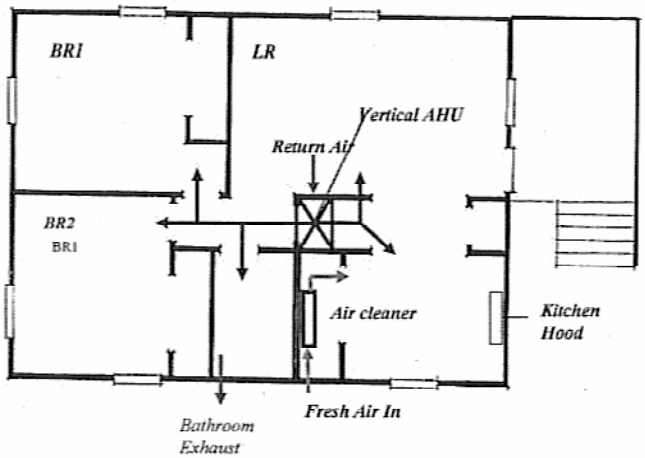

Figure 1 Floor plan of the ORNL-Tuskegee healthy house.

—VOC-free paints (no vinyl wall covering)
—Landscaping using plants that minimize pollen and other allergens

- Construction methods
  —To minimize stack effect, use one sealed ceiling penetration for vent stack; use wall-mounted lighting fixtures
  —A single plumbing wall to minimize floor penetrations and save costs; all floor penetrations completely sealed
  —Well sealed windows and door to lower infiltration
  —Exterior walls designed to dry to inside; no vapor barrier at drywall
  —Sealed attic and crawlspace from conditioned space
- Equipment
  —A single plumbing wall to minimize floor penetrations and save costs
  —115 cfm capacity turbulent flow precipitation (TFP) air cleaner (smallest commercially available unit) provided to filter particles larger than 0.3 μm (micrometers) from the fresh air intake
  —Centrally located heat pump air-handling unit to minimize ductwork
  —Ducts located within the conditioned space
  —All appliances are electric; no combustion equipment used

INSTRUMENTATION AND DATA ACQUISITION

Measurements of key IAQ parameters have been made using sensors and loggers that were configured for automated data acquisition. The attic, crawlspace, and living room were monitored for temperature and relative humidity. The carbon dioxide (CO_2) levels in the living room were measured at 3 ft above floor level. O_2, VOC, combustible gases (measured as percentage of lower explosive level, LEL), and carbon monoxide (CO) were also measured in the living room at 3 ft above floor level. The airborne particulate monitor was also installed in the living room. A data acquisition unit was used to collect data from the monitors and download it to a laptop for processing. (Additional details about the instrumentation are located in Appendix A.)

EXPERIMENTAL RESULTS AND DISCUSSION

Heating Season IAQ Characteristics and Energy Consumption

In order to establish a baseline, initial tests of the house were conducted with the house unoccupied and unfurnished. During the first week of heating season monitoring (Feb. 8-15, 2002), measurements were taken without running the filtered fresh air ventilation fan. CO_2 levels ranged from 380 to 460 ppm (typical outdoor is 300 to 500 ppm), and VOCs were measured at the optimal level. The electrical meter indicated that 84 kWh had been expended during the week. For these first two weeks of monitoring, all electricity consuming devices except the heat pump and the data logger were turned off. (The particulate meter had not yet been installed.)

During the second week of monitoring (Feb. 15-22, 2002), the fresh air ventilation fan with HEPA filter was turned on and kept on for the entire one-week period. The ventilation fan is rated at 125-130 cfm. (There were a limited number of sizes of ventilation fans with HEPA filters available. The one selected—the smallest commercially available at the time—was intended for a 2000-ft^2 house. ASHRAE recommends a minimum of 15 cfm [7.5 L/s] per person, or 60 cfm for a family of four, which this structure was designed to house.) Measurements were again taken and readouts were similar to the previous week. CO_2 levels were the same as the previous week—380 to 460 ppm. VOCs were measured at optimal levels again. The electrical meter showed that 107 kWh had been expended during the previous week.

During the first week, the outdoor temperature was an average of 5°F lower than during the second week, and yet energy consumption was 27% higher during the second week, as would be expected. Outside RH was comparable for the two weeks, but during the first week, inside RH ranged from 33% to 47%. The EPA and the Consumer Product Safety Commission (CPSC) recommend maintaining indoor RH levels between 30% and 50%. If humidity is too low, viral and bacterial populations tend to flourish, thus contributing to respiratory infections. If humidity is too high, fungal growth and dust mites can thrive, which can also contribute to health problems. During the second week when the ventilation fan was running, indoor relative humidity was reflective of outdoor humidity. Over half of the time during the second week, indoor relative humidity was measured either above or below the 30%-50% recommended optimum range.

The first two weeks of monitoring have provided preliminary evidence that running a ventilation fan 100% of the time does not improve indoor air quality in an unoccupied house. In fact, it contributed to indoor RH levels outside the recommended optimum range. Furthermore, running the ventilation fan led to significantly higher energy consumption due to the

when the windows were left open. The average dust concentration inside the house during the week when the windows were open was 0.04 mg/m^3 (0.022 ppm (v)). When the TFP air cleaner was on, dust concentration was 0.015 mg/m^3 (0.0083 ppm (v)), which is only 37.5% of the dust concentration with the windows open. The TFP air cleaner filters out particles that are greater than 0.3 µm in diameter. Most pollen spores have diameters larger than 20 µm. (While the air cleaner can filter out most particles of pollen that would enter the house through the fresh air fan, it does nothing to prevent entry of pollen through opened windows or doors. The filter will not remove these particles once they have entered because it is connected only to the fresh air supply.) Running the air cleaner during the swing season consumed an average of 3 kWh per day. (At $0.07 per kWh, this translates to $6.30 per month, a fairly nominal recurring expense.) Using the TFP air cleaner in the house did improve indoor air quality relative to particulates during the swing season, and it cost little to operate. However, the fresh air fan did not maintain RH within the desired range of 30 to 50%.

Impacts of High-Occupancy Conditions

The IAQ and efficacy of the ventilation system during high-occupancy conditions were evaluated next. Stable pretest conditions of indoor temperature and RH were established by air-conditioning/cooling the indoor air. The TFP air cleaner was kept running with the AC unit for 24 hours prior to starting the test. The high-occupancy condition was established by having 19 people inside the living room involved in sedentary activity (i.e., watching an educational video). The high occupancy was abruptly terminated after 80 minutes. During the high-occupancy period, the data acquisition systems recorded the temperature, RH, O_2, CO_2, particulate concentrations, and VOCs every five minutes. The measurements were continued for another 20 hours after the termination of the high-occupancy test.

Figure 4a shows RH during a 22-hour period that encompasses the high-occupancy event. As would be expected, a spike in RH is evident soon after the start of the high-occupancy period. Figure 4b shows the RH rising at the beginning of the crush load and dropping gradually during the occupancy period. The 1.5-ton heat pump brought RH back down to around 50%. The periodic spikes in the indoor RH (Figure 4a) are the kick-in signature of the AC unit. Figure 4a also reveals that the indoor RH in the living space (except during the high-occupancy period) reflects the outdoor RH when the TFP air cleaner was on—except at a much lower magnitude. The noticeable spike in the outdoor RH in Figure 4a was due to light rain after the test was completed. The AC coil maintained the indoor RH below 60% even when the outdoor RH approached 97%. At about 70% outdoor RH, the indoor RH was kept at about 50%. In the current experiment, the fresh air supplied to the house through the TFP air cleaner is 115 cfm. The amount of fresh air recommended by ASHRAE for residences based on two occupants is 30 cfm. Assuming that the condensation performance of the cooling coil is linear and 30 cfm is used instead of the 115 cfm, the indoor RH would be at about 53% for an outdoor RH of 97%. Thus, excluding the transient increase in RH due to occupancy, the indoor RH can be kept below 55% without the need for humidity control fulfilling the health house criteria.

Figure 5 illustrates the impact of high occupancy on O_2. A reduction in O_2 from 21.6% to 21.3% is observed during the test period of 80 min. The continuous depletion during the test period is attributed to the ventilation rate for the number of people inside the house. The ventilation supply was 3 L/s per person (6 cfm per person) in comparison with the current ASHRAE recommendation of 7.5 L/s per person (15 cfm person). It took about 90 min from terminating the test for the O_2 level to return to its original value of 21.6%. The 0.3% reduction in the O_2 level is not significant enough to cause concern. According to NIOSH (NIOSH, DHHS Pub. 87-113, 1987), oxygen levels below 19% can have health effects. Even the reduced ventilation supply rate per person was sufficient to

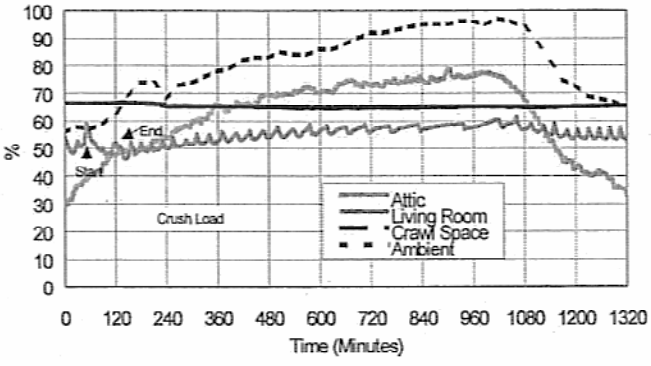

Figure 4a Relative humidity over 22 hours surrounding high occupancy.

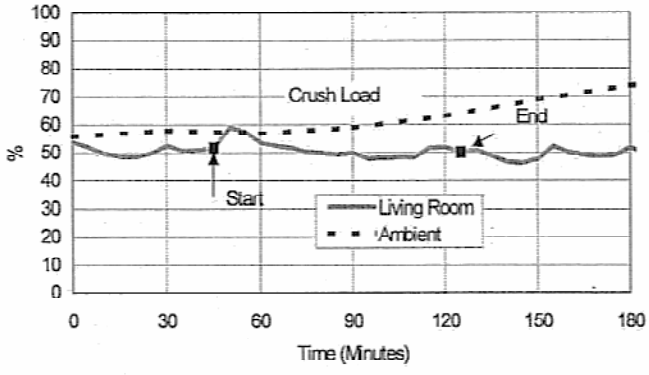

Figure 4b Relative humidity over three hours surrounding high occupancy.

During periods of rain and external high humidity, the addition of the filtered fresh air in the unoccupied house resulted in a significant increase of interior relative humidity that approached 60%. (In an occupied house, the addition of filtered fresh air could be anticipated to raise the relative humidity even higher.) During dry periods outside, the addition of filtered fresh air dropped the interior humidity to below 30%. With the fan running, there were only limited periods when the RH was in the optimum 30% to 50% range for health and comfort.

The addition of occupants is expected to raise the interior RH by perhaps 15% to 25%, depending on the occupants' lifestyle. This could potentially result in an interior RH range of 45% to 75%, well above the optimum for health and comfort. Such an elevated RH level would enhance the potential for mold and dust mite problems within the dwelling. The current configuration of the HVAC system makes no provision for removal of excessive interior moisture during the heating season or during the cooling season when external temperatures are near the thermostat setpoint, i.e., the air conditioner is not running. Additional study is needed to determine if, and to what extent, the addition of filtered fresh air could contribute to interior moisture problems during the heating season.

During the swing season, leaving the windows open resulted in about the same relative humidity in the house as using the fresh air fan. The only parameter with noticeably different readings was particulates. While particulate levels were lower when the fan was used, all particulate readings throughout both weeks were quite low. Using the fresh air fan in the swing season was of nominal cost but also nominal benefit compared to opening the windows. During the cooling season, the operation of both air conditioning and the filtered fresh air fan maintained acceptable air quality during crush loading.

Initial tests of the Tuskegee healthy house do indicate that meeting the sometimes competing priorities of affordability, energy efficiency, and IAQ will require a more balanced combination of system operation than simply keeping the ventilation turned on. Future tests will help to find a balance that best optimizes the combination of affordability, energy efficiency, and IAQ.

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DISCUSSION

Michael Heidenreich, Senior Principal Engineer, Advanced Heat Transfer LLC, Memphis, Tenn.: Did you compare the energy consumption between concrete slab construction and the unvented crawl space used in the actual model?

Heshmat A. Aglan: No we did not.

Jason Leroy, Trane, Tyler, Texas: Did you compare energy bills with ventilation vs. no ventialtion?

Aglan: Yes, the cost of ventilation alone was about $6 per month.

Use of fresh air fan at 115 cfm increased heating and cooling *total* energy use: