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Effect of mechanically induced ventilation on the indoor air quality of building envelopes

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ABSTRACT

Experiments were conducted to study the effect of mechanically induced fresh-air ventilation on the indoor air quality (IAQ) of the Tuskegee Healthy House (THH), selecting the outdoor weather conditions almost identical during the “fan OFF” and “fan ON” periods. Measurements of outdoor and indoor temperature and relative humidity (RH), in addition to the indoor dust particle concentration levels and interior wall moisture content, were systematically carried out during the summer month of August 2008. Results show that the effect of mechanically induced ventilation (“fan ON” period) is to raise the indoor RH, interior wall moisture content, and indoor dust particle concentration values significantly above those measured during the “fan OFF” period. The indoor temperature increases only slightly during the “fan ON” period.

1. Introduction

Indoor air quality (IAQ) is an important factor for every person living in a building. Since people in USA spend more than 90% of their lives in indoor [1], many studies have focused on the indoor air quality in residences, offices, schools, theatres, and large halls [2–6]. Indoor air quality depends on the different parameters such as the outdoor air, the building location, number of people, and the ventilation system in the building. In both mechanical and natural ventilated buildings, the indoor air quality mainly depends on the outdoor air [6]. The ventilation system in the building improves the indoor air quality and at the same time it increases the cost of power consumption. The optimum ventilation level depends on the source strength of the air pollution [7]. The mechanically induced ventilation rate also depends on the number of people living in the building. School and theatre buildings need high ventilation rates because of high-occupancy density compared to a typical residence [4,5].

Indoor air relative humidity level (RH) is also a measure of indoor air quality [8]. By definition, higher relative humidity means higher moisture content (MC). Moisture in building envelopes can cause numerous problems, including the indoor air quality, of mold/fungi and bacteria growth, various health hazards for the occupants, infestation by insects, and deterioration of the building components [9,10]. The Environmental Protection Agency (EPA) and the Consumer Product Safety Commission (CPSC) recommend maintaining indoor RH levels between 30% and 50% [11]. It is a common experience to notice that, in comfort-controlled buildings using HVAC (heat, ventilation, and air-conditioning) systems, the indoor RH goes down during winter season leading to dryness of the skin, etc. and it slightly increases during summer season leading to humid and sweaty conditions. If the humidity is too low, viral and bacterial populations tend to flourish, thus contributing to respiratory infections. If the RH is too high, fungal growth and dust mites can also contribute to health problems. Therefore, it is very important to maintain the indoor RH at the above-recommended optimum range [9–11].

A team of researchers at Tuskegee University has built a low-cost, energy-efficient, one-level test house, called the Tuskegee Healthy House (THH) [12], to conduct research on various aspects of the dwelling conditions and durability of a building. The THH is designed for a conventional family of four. A brief description of the THH will be given later.

Tuskegee is situated in the south-eastern region the United States of America where summer season is usually harsh (temperatures in the range of 90–104 °F or 32–40 °C with high RH). Research studies have been going on for the past 7 years to address several aspects of dwelling pertaining to THH. This test house incorporates a separate fresh-air ventilation system, in addition to a 1.5-ton heat pump, to provide extra air for additional occupants of the house. It was noticed during the outdoor and indoor measurements in the summer months of May–August 2008

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that the indoor RH, wall moisture content, and dust particle concentration levels had significantly changed, particularly during the period when the ventilation fan was running, although the average outside temperature and RH values always remained higher than those inside. The inside temperature was maintained at 71.6 °F (22 °C) by the house air-conditioner, but a slight increase in the value was noticed when the ventilation fan was running. The outside weather data were collected from a weather station situated about 200 yards (183 m) away from the test house.

Thus, the research study during these summer months showed that mechanically induced ventilation had some effect on the indoor air quality of the test house. The purpose of this paper, therefore, is to present in detail various aspects of the experiment and the results, and to discuss the effects of forced ventilation on the IAQ of building envelopes.

The present work is different from other investigations in the sense that nearly identical outdoor weather conditions during "fan OFF" and "fan ON" are considered to determine the effect of mechanically induced ventilation on the indoor air quality of a small residential house designed for a family of four. Wendt et al. [11] reported the indoor air quality of the THH using measurements made during winter 2002 for a two-week period. However, their measurements were based on the average values of the outside weather conditions and not on identical weather profiles. Parent et al. [7] conducted a one-week study of indoor air quality of 30 single-family detached houses to determine the optimum ventilation and air flow control requirements during 1993–94 winter season. This study was based on a blower-door test at 50 Pa and five different ventilation systems. Indoor CO_2 concentration levels and relative humidity were measured to determine the optimum ventilation requirements for different occupancy hours in the master bedroom. No outside weather data were reported in their work.

Studies on mechanically induced ventilation effects on the IAQ of some office buildings have been reported; but the investigations are different from the present work. For example, Rey and Velasco [2] conducted experimental study for a 15-day period in May 1997 to come up with recommendations for ventilation norms for the indoor air quality of office buildings equipped with different climatization systems using photo-acoustic spectroscopy and sulphur hexafluoride trace gas technique. Hummelgaard et al. [13] reported indoor air quality and occupant satisfaction in five mechanically ventilated and four naturally ventilated open-plan office buildings based on occupants' survey and measurements of indoor temperature and CO_2 for one week during October 2004. They reported slightly higher concentration levels of CO_2 with naturally ventilated buildings. No details about the outdoor weather conditions were discussed in either work.

Other high-occupancy commercial buildings, such as theaters, schools, and athletic halls, have also been studied; but they are different from the present work. For example, Kavgic et al [4] studied indoor air quality and thermal comfort in a mechanically ventilated theater for different levels of occupancy and ventilation rates. They reported the comfort levels of the occupants and ventilation rates at different parts of the theater with no discussion of the outdoor weather conditions. Clements-Croome et al. [5] made case studies of ventilation rates required in schools to improve the indoor air quality that affects students' health and classroom performance with no discussion of the outside weather conditions or the mechanically induced ventilation systems. They proposed a methodology to investigate the relationship between ventilation rates and student learning. In winter 1996, Kukadia and Palmer [6] conducted a pilot study over a one-week period to investigate and compare the internal and external air pollution levels of two adjacent office buildings in an urban area, one naturally ventilated and the other air-conditioned. They found no clear distinction between the two ventilation strategies in providing adequate indoor air quality for the occupants. Stathopoulou et al. [14] conducted an experimental study of the air quality inside two large athletic halls during February–March 2002 and reported that the air quality depended on the type of ventilation. They discussed only about the indoor and outdoor concentration levels of O_3, NO, and NO_2 during "events" and "no events" periods in the halls. Identical outdoor weather conditions, as described in the present work, were not considered in any of the above investigations.

2. The Tuskegee Healthy House (THH)

As mentioned above, a team of researchers from Tuskegee University's College of Engineering, Architecture and Physical Sciences, Tuskegee, Alabama, has designed and constructed a "healthy house." The team's goal was to develop a prototypical house that balanced the often competing values of affordability, energy efficiency, and indoor air quality. The result was a one-level 24 ft × 32 ft (7.32 m × 9.75 m) or 768 ft^2 (71 m^2) house located at Tuskegee's experiment station farm. The floor-to-ceiling height is 8 ft (2.44 m) giving a house volume of about 6, 144 ft^3 (174 m^3). The house has two bedrooms, one bath, a dine-in-kitchen, a living room, and small utility areas. A schematic of the Tuskegee Healthy House floor plan is shown in Fig. 1. The house is built on a crawlspace which is enclosed to minimize migration of moisture from the ground to the living area of the house. A 1.5-ton heat pump (HVAC) system provides for the heating and air-conditioning of the house. The front of the house is somewhat facing the south direction. The outer walls of THH consist of four layers: 1/16" (0.159 cm) vinyl siding, 3/4" (1.905 cm) foam board sheathing, 3.5" (8.89 cm) R-19 fiberglass batt insulation, and 1/2" (1.27 cm) gypsum board as shown in Fig. 2. The gypsum board forms the interior face of the walls.

As stated before, the test house incorporates a separate fresh-air ventilation system, in addition to the heat pump system, to provide extra air for additional occupants of the house. The house is designed for a family of four. The fresh-air ventilation fan is a 'LifeBreath' turbulent flow precipitation (TFP) air cleaner provided to filter particles larger than 0.3 μm from the fresh-air intake and is rated at 60 cfm (28.3 L/s). The fan power switch has only two positions, OFF and ON. A detailed discussion of the house construction, the IAQ, and the thermal performance characteristics of this house can be found elsewhere [10–12,15,16].

3. Instrumentation and data acquisition

Measurements of important IAQ parameters, such as temperature and RH, were made using sensors and data loggers that were configured for automatic data acquisition. Dual temperature/relative humidity sensors (Vaisala Model HMW60U/Y-U190en-1.2) were used to monitor the indoor conditions in the living room. The living room sensor is placed at a central location on a table about 3 ft (0.92 m) above the floor. The temperature measurement accuracy of the sensor is ±0.9 °F (±0.5 °C) for a range of −23 °F to +131 °F (−5 °C to + 55 °C) with linearity better than 0.18 °F (0.1 °C). The RH measurement accuracy for the sensor is ±3% over the range of 0–95% and has temperature dependence between 50 °F and 104 °F (10–40 °C) for a variation of the RH less than 0.5%. The output voltages from the temperature and RH sensors were scanned by an Agilent Technologies Model 34970 Data Acquisition/Switch Unit. This unit has a storage capacity of 50,000 scans with programmable scanning rates [11,15]. The outdoor temperature and RH data were downloaded from the weather station outside the house as mentioned earlier.

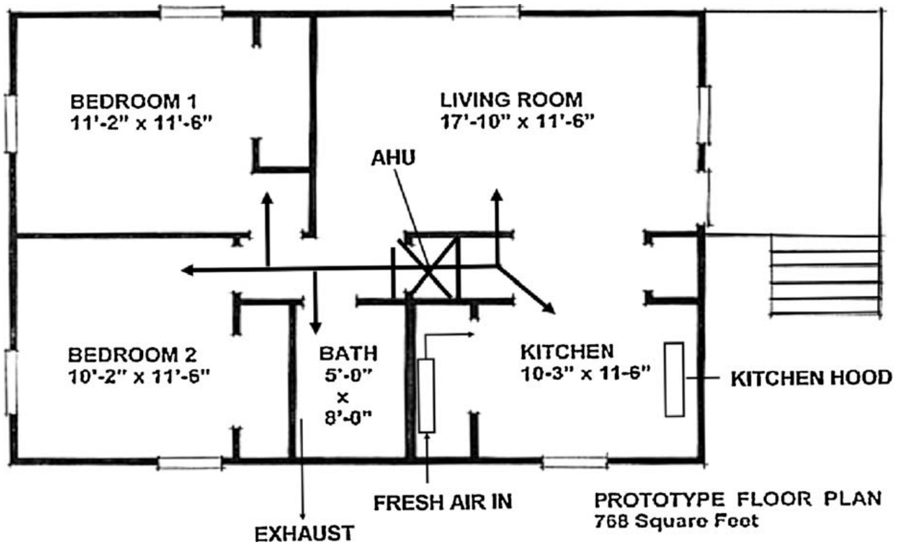

Fig. 1. Floor plan of THH.

A TSI Corp DustTrak Aerosol Monitor Model 8520 with a particle size range of 0.1–10 μm was used to measure the airborne particulate concentrations. It was located in the living room at 3 ft (0.92 m) above the floor. It has a resolution of ±0.1% of the reading and a stability of ±0.001 mg/m^3 over 24 h. The built-in data logger has a storage capacity of more than 31,000 data points (21 days logging every minute) and the logging interval can be adjusted between 1 s and 1 h. Data from DustTrak 8520 and the Agilent 34970 were periodically downloaded via RS232 to a notebook computer for post-processing.

A hand-held moisture meter (TRAMEX Survey Encounter) was used to measure the interior wall moisture content. This meter is specifically designed for measuring wood moisture content but, with proper care on settings and usage, could be used for other construction materials also, specifically for gypsum board walls as in the present experiment. The accuracy of the meter could not be determined in this study. However, this meter gives a relative number for the moisture content depending on the RH and it must be calibrated to get the MC versus RH characteristics. Several small samples (6″ × 4″) were cut from of 1/2-in gypsum board to carry out the calibration process in a humidity-controlled test chamber. The MC in % was based on the dry weight of the samples. The limitations on the humidity control of the chamber restricted the number of calibration data points that could be obtained in this study. The calibration curve of MC (in %) versus RH obtained in this work is as shown in Fig. 3 and it is very similar to the one found in Ref. [17]. Fig. 4 shows the actual moisture content (MC %) versus the meter reading. The linear relation between MC and the meter reading shown in Fig. 4 was used to determine the moisture content of gypsum wallboards in this study.

4. Experimental procedure

Measurements of various parameters (temperature, RH, dust particle concentration, moisture content, and power consumption) for the THH were carried out for a two-week period during the summer month of August 2008 alternating the fresh-air ventilation fan “OFF” and “ON” conditions, each for at least two days, during the measurement, i.e. the fan was “OFF” on days 1–3, and “ON” on days 4–6, “OFF” on days 7–9, and “ON” on days 10–12. With this schedule, the data from the last two days of each condition (i.e. days 2–3, 5–6, etc.) only were considered for analysis. The first day of each case (day 1, 4, etc.) was allowed to reach the equilibrium state before indoor measurements were made. This would give the house a chance to shift from less to more humid condition and vice versa. During the time when the fresh-air ventilation fan was “ON”, it was running at 60 cfm (28.3 L/s) capacity. The HVAC system (air-conditioner) was running in the “AUTO” mode with the thermostat set at 71.6 °F (22 °C) during the measurement periods. It should be noted that, during these measurement periods, no occupants were present in the house; however, there were new furniture items, still in their original packages, lying in the living room and in one of the bedrooms.

The hourly outdoor data of temperature and RH were collected by the weather station situated outside THH and the hourly indoor air quality data (temperature, RH, and dust particle concentration)

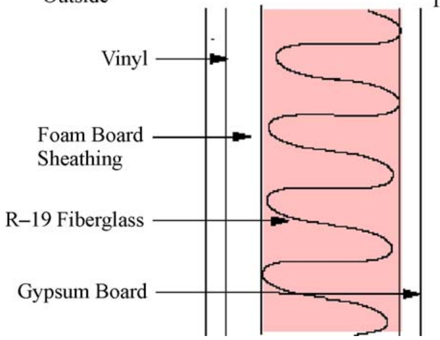

Fig. 2. Cross-section of THH outer wall.

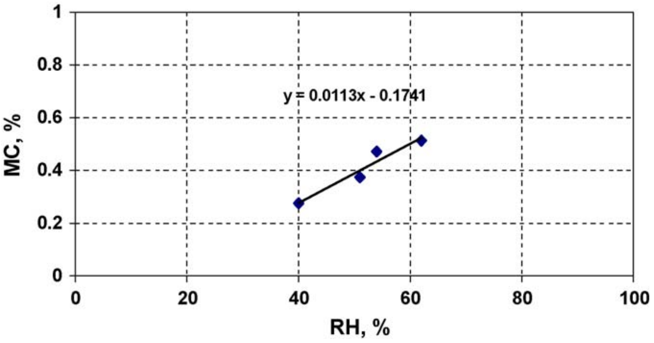

Fig. 3. Calibration curve for the hand-held moisture meter, MC vs RH.

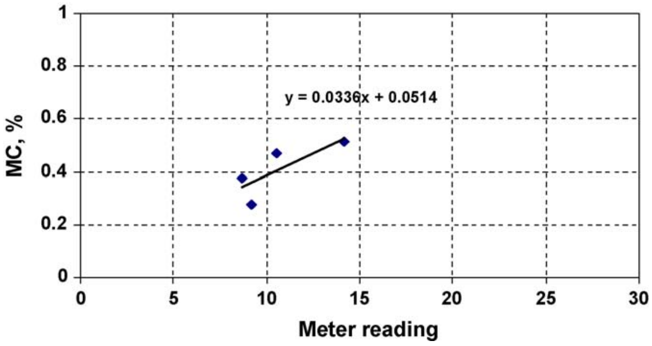

Fig. 4. Calibration curve for the hand-held moisture meter, MC vs meter reading.

were collected by the data acquisition system described earlier. The moisture content at several locations on each of the interior surface of the four (North, South, East, and West) enclosing walls of THH was measured using the hand-held moisture meter mentioned above. The moisture content was measured at the same previously marked wall locations for each case of the test runs. The moisture content measurements were made twice (9 am and 3 pm) during the day of the test run. The electric power (KWh) consumption per day (24-h period) was measured by reading the watt-hour meter situated outside THH exactly at the same time every day (9 am and 3 pm) during the test runs. The data collected were processed on a personal computer. The results are presented below.

5. Results and discussion

The objective of this work was to determine the effect of forced ventilation on the IAQ of THH for a given outdoor weather condition. It was hoped from the test runs that the outdoor weather data would be very similar or nearly identical during both the fresh-air ventilation "fan OFF" and "fan ON" conditions, but this was not the case in the present study (see Figs. 5 and 6). Unfortunately, due to day-to-day variations (rain, wind, etc.) in the weather condition, the outdoor measurements of all the runs showed that only four sets of weather data (two during "fan OFF" and two during "fan ON") matched very closely. Hence, the weather data of these four days only are considered here for evaluating the changes in the indoor air quality due to forced ventilation in the THH. The results of temperature, RH, dust particle concentration, and power consumption data during the "fan OFF" and "fan ON" periods are presented and discussed in the following paragraphs.

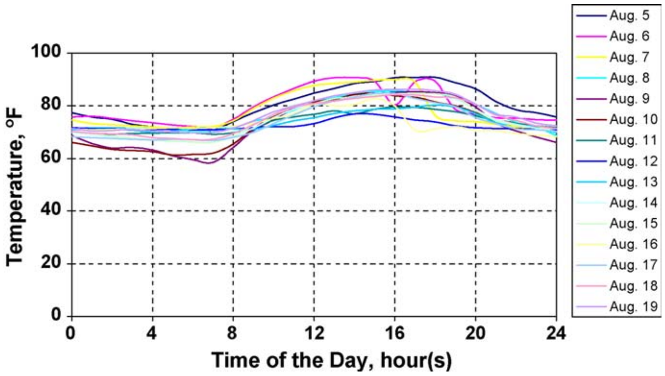

Fig. 5. Overlay of outdoor hourly temperature variations during the two-week measurement period (includes both fan OFF and fan ON periods).

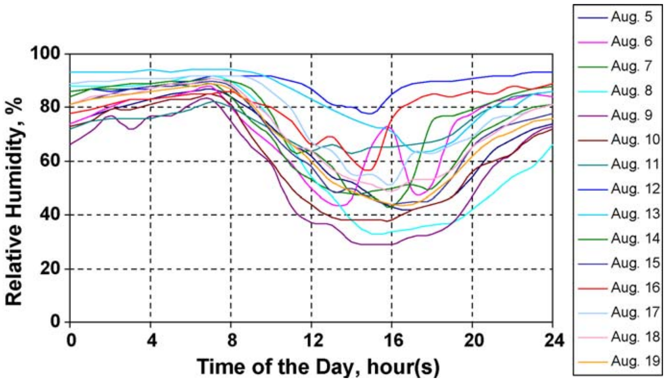

Fig. 6. Overlay of outdoor hourly RH variations during the two-week measurement period (includes both fan OFF and fan ON periods).

5.1. Temperature data

Fig. 7 shows the 24-h plots of temperature profiles for the "fan OFF" and "fan ON" periods August 14, 2008 and August 18, 2008, respectively. Fig. 8 shows similar plots for the "fan OFF" and "fan ON" periods August 15, 2008 and August 19, 2008, respectively. These figures are very similar and are plotted separately to avoid clutter of the data and to show specifically how in each case the outdoor weather data match very closely for the "fan OFF" and "fan ON" periods. Both outdoor and indoor profiles are plotted on the same graph for comparison purpose. These plots also show the hour-to-hour variations of the indoor and outdoor temperatures during the two periods. (Note in these plots, 0 and 24 h on the *x* (or time) axis represent the beginning and the end of the day, i.e. midnight and 12 h represents the noon time.)

Fig. 7 shows that the outdoor temperature profiles are very identical. The overall outdoor average temperature for the "fan OFF" period is calculated to be 74.72 °F (23.73 °C) and for the "fan ON" period 75.39 °F (24.11 °C) and they match within 1 °F (0.55 °C). The indoor temperature profiles in this figure are seen to be very uniform throughout the day. This is expected because the inside temperature is controlled by the house air-conditioner (HVAC) system. The overall average temperature is calculated to be 72.06 °F (22.26 °C) for the "fan OFF" period and 73.24 °F (22.91 °C) for the "fan ON" period. Thus, on the average, the indoor temperature has risen by 1.18 °F (0.65 °C) when the fresh-air ventilation fan is running.

Fig. 8 shows a very similar behavior of temperature to that in Fig. 5. The overall average outdoor temperature in this case is calculated to be 75.22 °F (24.01 °C) for the "fan OFF" period and 76.99 °F (24.99 °C) for the "fan ON" period and they match within

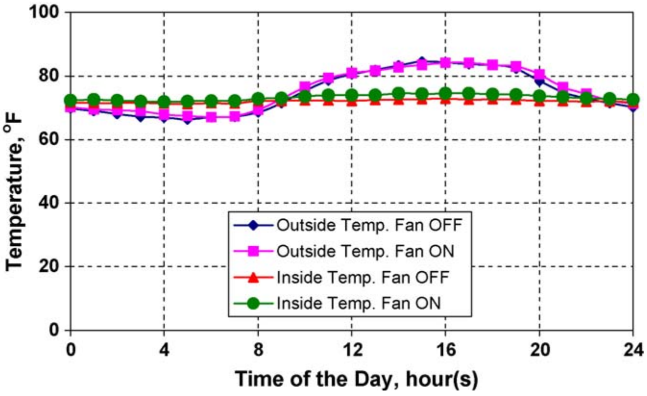

Fig. 7. Hourly variation of outdoor and indoor temperature during "fan OFF" (August 14) and "fan ON" (August 18) period.

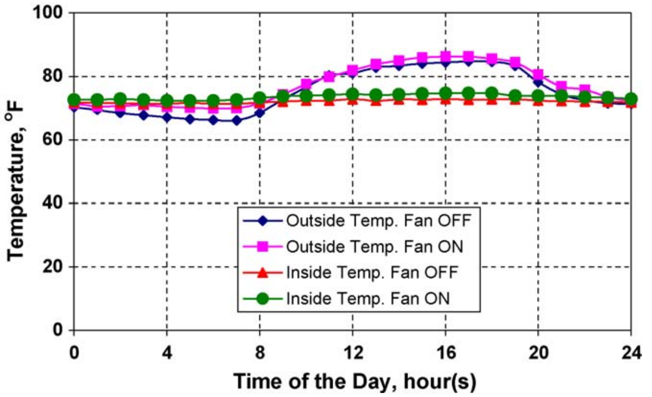

Fig. 8. Hourly variation of outdoor and indoor temperature during "fan OFF" (August 15) and "fan ON" (August 19) period.

2 °F (1.11 °C). Again, as expected, the indoor temperature profiles in this figure are seen to be very uniform throughout the day. The overall average indoor temperature for the "fan OFF" period is calculated to be 72.08 °F (22.27 °C) and 73.52 °F (23.07 °C) for the "fan ON" period, indicating on the average that the indoor temperature has risen by 1.44 °F (0.80 °C) when the ventilation fan is on. Thus, it is observed from these results that, given the same outside temperature profiles, the effect of forced ventilation is to raise the HVAC-controlled inside temperature by about 1.0–1.5 °F (0.55–0.83 °C).

Figs. 7 and 8 also show that lower outdoor temperatures (equal to or lower than the indoor average temperature) occur during the late evening and early morning hours (between 10 pm and 7 am) and those higher than the average indoor temperature occur during the late morning and afternoon hours (between 10 am and 8 pm). The lowest outdoor temperature during the measurement period is seen to be around 66 °F (18.9 °C) and the maximum around 85 °F (29.4 °C). Thus, these plots indicate that there exists a strong temperature gradient across the THH walls mostly in the afternoon hours on any given day during the summer time.

5.2. Relative humidity data

Fig. 9 shows the 24-h plots of RH profiles for the "fan OFF" and "fan ON" periods August 14, 2008 and August 18, 2008, respectively. Fig. 10 shows similar plots for the "fan OFF" and "fan ON" periods August 15, 2008 and August 19, 2008, respectively. These figures are very similar to the temperature profiles discussed above and are plotted separately to show that in each case the outdoor weather data specifically match very closely for the "fan OFF" and "fan ON" periods. These plots also show the hour-to-hour variations of the indoor and outdoor RH during the two periods.

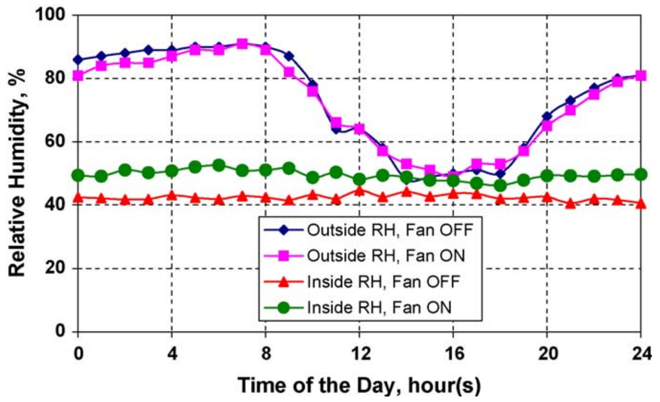

Fig. 9. Hourly variation of outdoor and indoor RH during "fan OFF" (August 14) and "fan ON" (August 18) period.

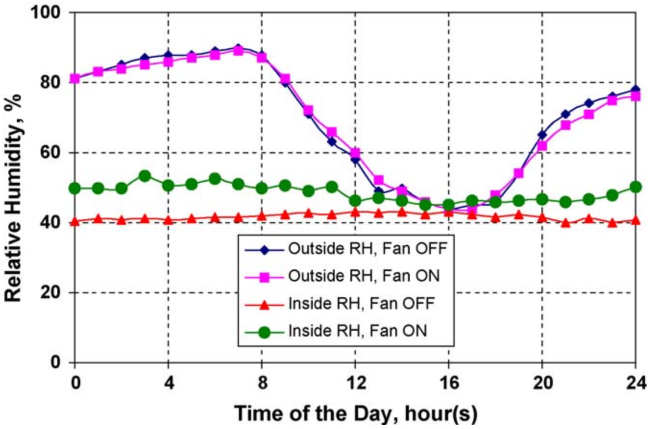

Fig. 10. Hourly variation of outdoor and indoor RH during "fan OFF" (August 15) and "fan ON" (August 19) period.

Fig. 9 shows that the outdoor RH profiles are almost identical. The overall average outdoor RH for the "fan OFF" period is calculated to be 73.44% and for the "fan ON" period 72.44% and they match within 1%. The indoor RH profiles in this figure are seen to be uniform throughout the day. The overall average inside RH is calculated to be 42.41% for the "fan OFF" period and 49.49% for the "fan ON" period. Thus, on the average, the indoor RH has risen by 7.08% when the fresh-air ventilation fan is running.

Fig. 10 shows a very similar behavior of RH as in Fig. 6. The overall outdoor average RH in this case is calculated to be 69.50% for the "fan OFF" period and 69.52% for the "fan ON" period and they match very well. Again, the indoor RH profiles in this figure are seen to be uniform throughout the day. The overall average indoor RH is calculated to be 41.70% for the "fan OFF" period and 48.50% for the "fan ON" period, indicating that, on the average, the indoor RH has risen by 6.80% when the ventilation fan is on. Thus, it is observed from these results that, given the same outside RH profiles, the effect of forced ventilation is to raise the inside RH by about 7.0%.

Figs. 9 and 10 also show that, during the measurement periods considered in this study, the outdoor RH is always higher than the indoor RH with the higher RH always occurring in the late night and early morning hours. Maximum outside RH of about 91% occurs around 7–8 am. The lowest outdoor RH of about 44% occurs around 4 pm. The outdoor RH varies inversely as a function of the outdoor temperature as shown by these plots. Thus, these plots indicate that there exists a strong moisture (RH) gradient across the THH walls mostly in the late night and early morning hours on any given day during the summer time.

5.3. Dust particle concentration data

Fig. 11 shows the measured hourly variations of the dust particle concentration levels during selected "fan OFF" and "fan ON" periods (which include August 14–15, August 18–19 also) in the present THH experiment. It may be recalled that the dust concentration level was measured in the living room only, 3 feet above the floor. It is seen from the results that there is a significant scatter and increase of the dust particle concentration levels during the "fan ON" periods when compared to those during "fan OFF" period, a factor which must be considered when evaluating the IAQ of building envelopes. The average concentration level during a 24-h period is calculated to be 0.0066 mg/m^3 for the "fan OFF" condition and 0.0266 mg/m^3 for the "fan ON" condition. Thus, there is a huge (about four-fold) increase of the dust particle

Table 1
Average values of temperature, RH, MC, dust particle level, and power consumption data for the THH during "fan OFF" and "fan ON" period.

Date	Outside		Inside		Average MC (%)				Average power (kWh/day)	Average dust level (mg/m^3)	Remarks
	Avg. temp. (°F)	Avg. RH (%)	Avg. temp. (°F)	Avg. RH (%)	E-wall	W-wall	N-wall	S-wall			
8/18/2008	75.39	72.44	73.24	49.49	0.74	0.70	0.64	0.95	30	0.0284	Fan ON
8/14/2008	74.72	73.44	72.06	42.41	0.61	0.52	0.50	0.78	24	0.0093	Fan OFF
Difference	0.67	−1.00	1.18	7.08	0.13	0.18	0.14	0.17	6	0.0191	
8/19/2008	76.99	69.52	73.52	48.50	0.76	0.67	0.65	0.93	32	0.0296	Fan ON
8/15/2008	75.22	69.5	72.08	41.70	0.49	0.46	0.45	0.68	24	0.0087	Fan OFF
Difference	1.77	0.02	1.44	6.80	0.27	0.21	0.20	0.25	8	0.0209	

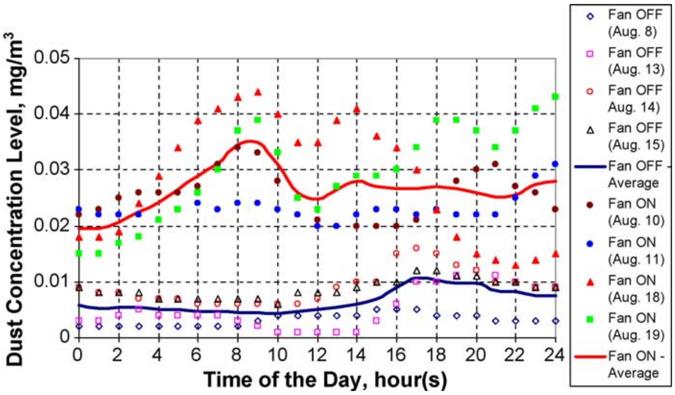

Fig. 11. Hourly variations of indoor dust concentration levels during "fan OFF" and "fan ON" period.

concentration level when the fresh-air ventilation fan is ON compared to that when it is OFF.

5.4. Moisture content data

The average moisture content (MC—expressed as %) on the interior surface of the four enclosing walls of THH measured during the "fan OFF" and "fan ON" periods are as shown in Table 1. The table also shows the corresponding average values of the outdoor and indoor temperatures and RH, average dust concentration levels, as well as the power consumption data, which will be discussed later. As can be seen, the MC values are always higher during the "fan ON" period than those during the "fan OFF" period. This is attributed to the increase in the indoor RH values during the "fan ON" period, which brings more moisture into the building. Also, the South wall exhibits higher MC values than other walls. Overall, under the same given outside and inside climatic conditions, there seems to be 20–50% increase in the MC values when the fresh-air ventilation fan is running compared to that when it is OFF.

5.5. Power consumption data

The 24-h period power consumption data obtained during the "fan OFF" and "fan ON" measurements periods considered in this study are shown in Table 1. The average power consumed per day is 24 kW for the "fan OFF" period and 31 kW for the "fan ON" period. Thus, keeping all the other conditions of operation of THH the same during both measurement periods (except for the ventilation fan), the average power consumed by the fresh-air fan alone is found to be 7 kW per day.

6. Conclusions

Experiments were conducted to study the effect of mechanically induced ventilation on the indoor air quality (IAQ) of the Tuskegee Healthy House (THH) situated in the south-eastern region of the United States. Systematic measurements of both outdoor and indoor climatic data, including the indoor dust particle concentration levels and interior wall moisture content, were performed for the fresh-air ventilation "fan OFF" and "fan ON" periods during the summer month of August 2008. Identical outdoor weather conditions were considered to determine the effect of forced fresh-air ventilation on the IAQ, i.e. only those outdoor temperature and RH data were selected which were very closely matching with one another during the "fan OFF" and "fan ON" periods. The results from the present study show that, under the same given outside and inside equilibrium climatic conditions for the THH, the mechanically induced ventilation:

(1) raises the inside temperature by about 1.0–1.5 °F (0.55–0.83 °C);
(2) raises the inside RH by about 7.0%;
(3) increases the dust particle concentration level by about four-fold;
(4) increases the interior wall moisture content values by 20–50%; and
(5) consumes about 7 kW (29%) of extra power per day (24 h).

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