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Temperature and power consumption measurements as a means for evaluating building thermal performance

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ABSTRACT

A simple methodology is introduced to obtain an empirical relation between power consumption and indoor–outdoor temperature variations for a small residential building. The effects of house occupants, air/moisture leakage, material deterioration, etc. were not considered in the analysis. The Tuskegee Healthy House was used as a test building for the experiment. Empirical equations for power consumption as a function of temperature area differences were obtained from the measured data of winter 2009 with and without mechanically-induced ventilation fresh air, i.e. using fan "ON" and fan "OFF" condition, respectively. The equations were applied to the measured temperature data of winter 2002 to compare and evaluate the thermal performance of the test house. The equations agree favorably with the winter 2002 data revealing that there is no significant difference in power consumption values of winter 2002 and winter 2009 and, hence, no appreciable change in the thermal performance of the house. The methodology presented in the work can be utilized to compare and evaluate the thermal performance of a given building envelope from season to season and between the same seasons in different years.

1. Introduction

Minimizing power consumption is one of the many aspects of energy conservation and economic operation of a building envelope. At the same time, maintaining a hourly/daily time-history of the power consumption data as a function of the indoor and outdoor climate conditions can serve as a good measuring tool for evaluating the thermal performance of a building envelope as it begins to age. The energy consumption depends upon different factors, such as the building construction type and the materials used (in walls, roof, floor, windows, door, etc.), the orientation of the building, outdoor climate, heating and cooling systems used, airtightness, type of insulation, lighting, ventilation, number of occupants, and many other variables. Thus, the thermal responses of building components and the thermophysical properties of building envelopes together determine the energy consumption behavior and comfort conditions of a building.

Because of the varied nature of building types, location, and climate the power consumption of a given building envelope varies with time as the building starts aging. Several studies dealing with any one or two individual aspects of energy conservation, such as the energy transmission through different types of wall construction, insulation material, effect of climate conditions, inhabitants have been reported [1–4]. Moisture content also affects the thermal resistance (*R*-value) of the insulation and other materials [5]. In the energy analysis of home constructions, because the insulation cannot be replaced without a major dismantling, the *R*-value is assumed to remain constant for many decades (20 years or more) [6–7].

Energy consumption is also affected by air leakage and air infiltration in the building. Literature review indicates that there is no linear correlation between air leakage and building age. It is found that a new building sometimes may have more leakage than the older ones [8–10]. Regular inspection of the building for any structural damage or deterioration, therefore, must be a part of the thermal performance evaluation process.

Combinations of analytical/modeling and experimental techniques are also used in practice sometimes to assess the thermal performance of a building [2–4]. But, from a point of view of just the power consumption alone, there is no specific methodology available that suggests how the thermal performance of a building varies as it starts aging.

The present study attempts to address this issue by presenting a methodology that involves measurements of power consumption as a function of indoor–outdoor temperature variations. The methodology is simple and it can be easily applied to any type of building envelope. The methodology is applied to a test house, called the Tuskegee Healthy House (THH), situated in the south-eastern region of the United States. A description of the THH is given in the next section. The study presented here includes measured power

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and weather data in the winter season of 2009. The methodology can be applied to other seasons also. Given the same inside operating conditions, the methodology can be used to compare and evaluate the thermal performance of a building envelope from season to season and between the same seasons in different years.

2. Tuskegee Healthy House

In order to address the energy efficiency and the indoor air quality in residential buildings, researchers at Tuskegee University, Alabama, have designed and constructed a ‘‘healthy house”. Three main criteria for the design and construction of the Tuskegee Healthy House were low cost, energy efficiency, and healthy indoor air quality (IAQ) [11]. Research studies to address the various issues related to thermal performance of this building have been reported elsewhere [12–14].

The one-story test house is built on a crawlspace. A schematic of the THH floor plan is shown in Fig. 1. A photograph of the house is given in Fig. 2. The area of the house is 24 ft × 32 ft (7.32 m × 9.75 m) or 768 ft^2 (71 m^2). The floor-to-ceiling height is 8 ft (2.44 m) and therefore the house volume is about 6144 ft^3 (174 m^3). The house has two bedrooms, one bath, a dine-in-kitchen, a living room, and small utility areas. The house has seven windows, six with dimensions of 3 ft × 5 ft (0.92 m × 1.52 m) and the other with 3 ft × 3 ft (0.92 m × 0.92 m).

The HVAC system is located in the center of the living space to minimize ductwork. The heat pump capacity is 1.5 ton. The 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 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 outer walls of THH consist of four layers: 1/16 in (0.159 cm) vinyl siding, ¾ in (1.905 cm) foam board sheathing, 3½ in (8.89 cm) *R*-19 fiberglass batt insulation, and ½ in (1.27 cm) gypsum board as shown in Fig. 3. Foam board is used for sheathing with thermal resistance of 5 (*R*-5) to provide a continuous layer of insulation as well as air and moisture barrier. There are two layers of *R*-19 fiberglass insulation placed in the attic. Several airtightness features are considered in the house construction to minimize leakage. The sheathing and framing are used to reduce the thermal loss and improve energy efficiency.

The crawlspace is based on a concrete masonry unit (CMU) foundation having the exterior wall footings filled with cement concrete mixture. The crawlspace floor is covered with 2 in. (0.05 m) of fine sand on top of a full-ground polyethylene vapor-retarding membrane. The crawlspace is enclosed and has a vent system that can be closed and opened as needed to minimize migration of air and moisture from the ground to the living area of the house and also to reduce energy loss through the house floor. The crawlspace is checked periodically for any formation of mold or mildew. The THH is inspected and maintained regularly to prevent any structural damage or degradation.

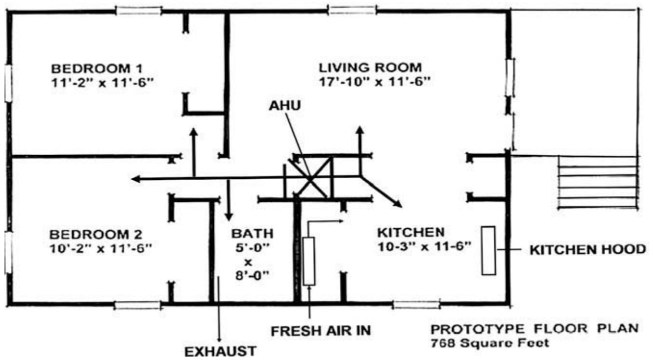

Fig. 1. Floor plan of Tuskegee Healthy House (THH).

Fig. 2. Photograph of THH.

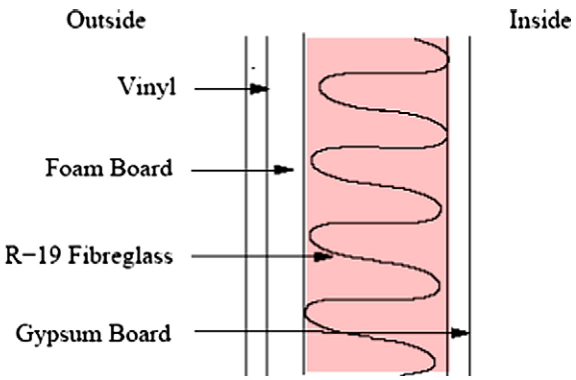

Fig. 3. Cross section of THH outer wall.

Off-the-shelf wall-mounted light fixtures are used to reduce penetration through the ceiling. The house has only one plumbing wall with one floor penetration. All ductwork and penetrations through the building envelope are sealed.

The THH is equipped with instrumentation and data acquisition systems to measure and record the indoor and outdoor climate conditions in addition to other indoor air quality parameters. The house energy consumption is measured using a conventional power meter situated outside the building. The instrumentation system is described in the next section.

3. Instrumentation

Dual temperature/relative humidity sensors (Vaisala Model HMW60U/Y-U190en-1.2) were used to measure and record the relative humidity (RH) and temperature inside the THH. The living room sensors were 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) and the relative humidity measurement accuracy for the sensor is ±3% over the range of 0–95% [13,14]. A desktop computer system with an Agilent Technologies model 34,970 data acquisition unit was used to monitor, check, calculate, integrate, and save

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the data acquired from the test building. The electric power consumption (kW h) per day was measured by reading the watt–hour meter situated outside the THH. The wattmeter has an accuracy of ±1 kW h.

The weather station, called "Health Enviro Monitor," located about 180 m from the THH was used to record the outdoor temperature and relative humidity. The Health Enviro Monitor comprises of two components: a sensor interface module (SIM) to which all-external sensors are connected and a console which performs A/D conversion, calculations, and display of data. This weather station stores air temperature and humidity, wind speed and direction, wind chill, solar radiation, barometric pressure, and rainfall data.

4. Methodology

The methodology presented here is specific to the Tuskegee Healthy House (THH) mentioned above and can be applied to other types of buildings also. The method involves measuring and recording the hourly variations of both indoor and outdoor temperature and the power consumption data for a number of days during a given season. The longer the data collection period, the better the correlation will be. Because most of the residential heat pump systems control the indoor temperature rather than the relative humidity, the temperature effects are only considered in the present study. The effects of occupants, air/moisture leakage, material deterioration, etc. are not considered in the analysis.

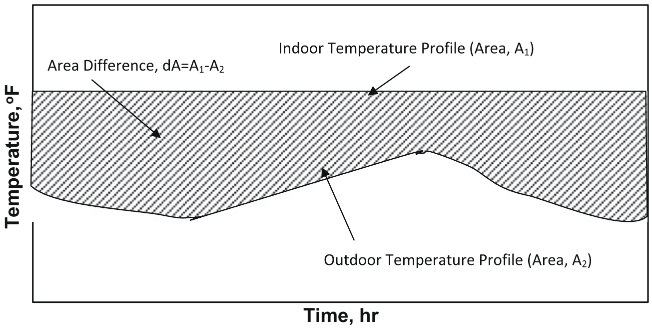
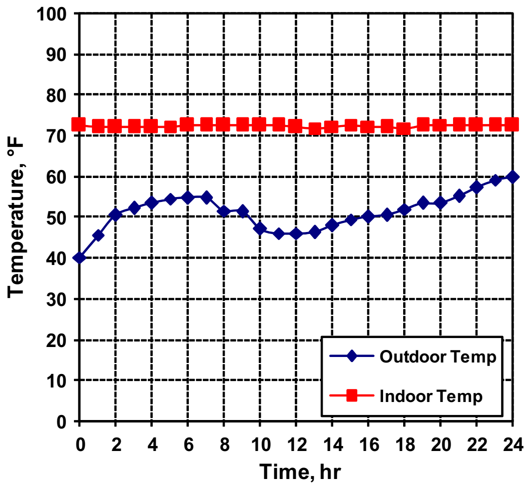


Fig. 4. Illustration of indoor–outdoor temperature profile areas $A1$, $A2$, and ΔA.

The method considers the profiles of indoor–outdoor temperature and overall power consumption data for a given time duration (for example, 24 h) as shown in Fig. 4. Fig. 4 refers to a situation in the winter season, in which heating is typically used and the outdoor temperature profile is assumed to be below the indoor temperature profile. The area under indoor temperature profile ($A1$) and the area under the outdoor temperature profile ($A2$) are computed using a suitable numerical technique, such as the trapezoidal or Simpson's rule of numerical integration. Then, the area difference (ΔA) between the two temperature profiles is determined from: $\Delta A = A1 - A2$, as illustrated in Fig. 4.

A sample computation of ΔA using actual indoor–outdoor temperature data from winter 2009 measurements without the mechanically-induced fresh-air ventilation (fan "OFF" condition) is given in Fig. 5. The hourly variations of the indoor–outdoor temperature over a 24-h time duration are shown in this figure. Using the trapezoidal rule, areas $A1$ and $A2$ are computed to be 1734.72 °F h and 1036.25 °F h, respectively, giving a value of $\Delta A = 698.47$ °F h. The size and area bounded by the shapes of the temperature profiles determines how long and at what level the heat pump system was active and working. This temperature area difference is different from one day to the other because of the variability in the outdoor weather conditions. Thus, given the same inside operating conditions of the house for certain time duration, the power consumption for that period is directly proportional to this area difference, ΔA. After computing ΔA for all the test runs in a given season, a graph of power consumption (P) versus ΔA can be plotted and an empirical relation between P and ΔA can

Time Duration (hr)	Outdoor Temp (°F)	Indoor Temp (°F)
0	40.30	72.53
1	45.80	72.12
2	50.60	72.09
3	52.40	72.00
4	53.60	72.23
5	54.60	72.27
6	54.80	72.43
7	54.70	72.58
8	51.70	72.61
9	51.40	72.59
10	47.10	72.49
11	46.10	72.41
12	46.10	72.19
13	46.50	71.95
14	48.20	72.30
15	49.60	72.77
16	50.20	72.34
17	50.60	72.19
18	52.10	71.90
19	53.50	72.42
20	53.60	72.75
21	55.20	72.53
22	57.30	72.42
23	59.30	72.41
24	59.90	72.54



Area under indoor temp profile, A1 = 1736.52 °F.hr
Area under outdoor temp profile, A2 = 1235.10 °F.hr
Area difference, ΔA = A2 - A1 = 501.42 °F.hr

Fig. 5. Sample data from fan "OFF" period of winter 2009 showing indoor–outdoor temperature profiles and sample calculation of temperature area difference ΔA.

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be established. This empirical equation can serve as a measuring tool to compare and evaluate the thermal performance of a given building envelope from one season to the next season under the same inside operating conditions.

5. Experimental measurements

Measurements of temperature, RH, power consumption, and other parameters for the THH were carried out during the winter months (January 16–March 09) of 2009, alternating the fresh-air ventilation "OFF" and "ON" conditions. The hourly indoor air quality data (temperature, RH, dust particle concentration, etc.) were collected by the data acquisition system described earlier. The indoor temperature was kept at about 72 °F (22.2 °C) during both fan "OFF" and fan "ON" periods and was controlled by the heat pump thermostat set in AUTO mode. The average indoor RH was about 27.50% for the fan "OFF" period and about 24.06% for the fan "ON" period. The fresh-air ventilation fan was running at 60 cfm (28.3 L/s) capacity during the fan "ON" condition. All the lights were turned off during the test period. No occupants were present in the house during the tests except for some new furniture items, still in their original packages, lying in the living room and in one of the bedrooms.

The hourly outdoor temperature and RH data were collected by the weather station situated outside the THH. It was noted that, during both the fan "OFF" and fan "ON" periods, the outdoor temperature was always lower than the indoor temperature. The power consumption, in kW h, was measured by reading the watt–hour meter situated outside the THH at about the same time every day during the test period. The data collected were processed on a personal computer. The results are presented in Section 7.

6. Power consumption by fresh-air ventilation fan and instrumentation and data collection systems

Experiments were conducted, separately, to determine the power consumed by the fresh-air ventilation fan and the instrumentation and data collection system. This was done by switching on and switching off the respective unit in proper sequence and taking readings off the power meter, while the heat pump was completely turned off. It was found that the fresh-air ventilation system alone consumed about 3 kW h/day. Based on the experiment and the individual instrument power rating, it was estimated that the instrumentation and data collection systems consumed about 1 kW h/day (approximately the same value reported in reference 14 also).

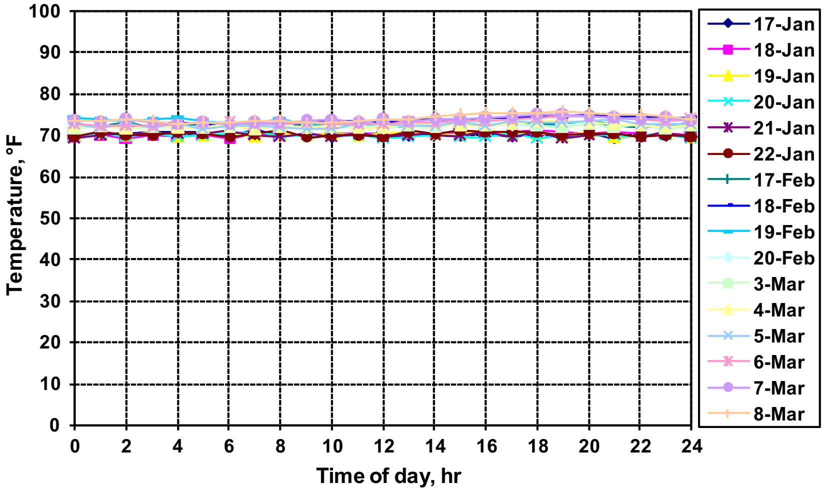

Fig. 6a. Indoor temperature profiles for the fan "OFF" period of winter 2009.

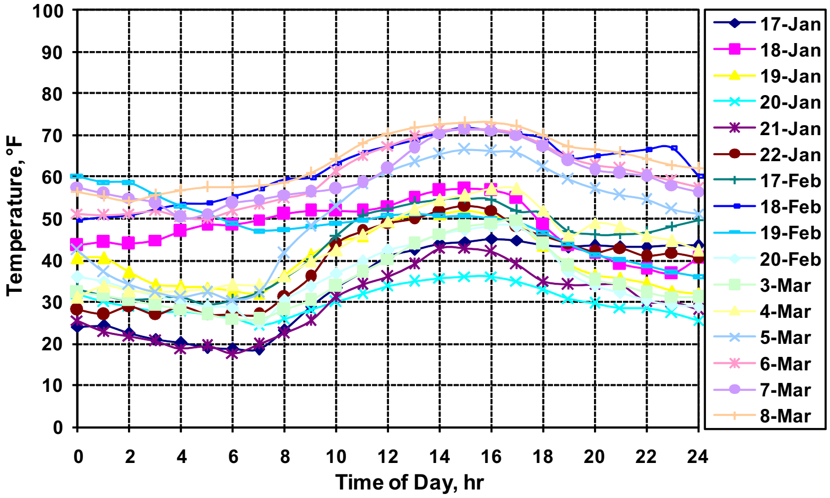

Fig. 6b. Outdoor temperature profiles for the fan "OFF" period of winter 2009.

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7. Results and discussion

The power consumption data for the THH measured during the winter months of 2009 with and without the mechanically-induced fresh air are presented and discussed in this section. The results are compared with the measured temperature and power consumption data of winter 2002 and an evaluation of the thermal performance of the THH building under similar inside operating conditions in the season is made.

7.1. Power consumption without mechanically-induced fresh-air ventilation (fan "OFF" period)

In the present study, the hourly variations of temperature and relative humidity were measured and recorded for a period of 18 days during the winter months January–March of 2009. The indoor and outdoor temperature profiles are as shown in Figs. 6a and 6b, respectively. In these figures, and in other similar figures to follow, "0" (also "24") on the time axis represents midnight and "12" the noon. The power meter was not equipped to record the hourly variations automatically. Instead, power consumption data, in kW h, were recorded manually twice, approximately around 9 am and 3 pm, on each day of testing by noting down the initial and final readings. The time duration, in hours, for which the power consumption data was valid, was also noted. The time duration was selected as 24 h in this study. If the time difference was different, then, only the corresponding (matching) parts of the temperature profiles were considered for area computation. If, for example, the power consumption data was obtained for a duration of 18 h from 3 am to 9 am the next day, only that part of the indoor–outdoor temperature profiles for which the power consumption data was valid, was considered for computing the area difference ΔA.

Table 1
Measured power consumption and ΔA data for the fan "OFF" period of winter 2009.

Data no.	Time duration (h)	Area diff. ΔA (°F h)	Power consumption (kW h)
1	22	750.41	24
2	25	616.79	17
3	18	611.41	15
4	24	740.06	18
5	24	501.42	13
6	24	410.32	11
7	18	272.37	10
8	24	288.57	8
9	24	385.68	10
10	24	767.26	20
11	24	815.96	22
12	18	660.47	17
13	24	886.77	23
14	18	704.19	18
15	24	875.42	26
16	26	888.13	23
17	22	619.60	15
18	24	383.47	12

The time duration, power consumption, and the corresponding ΔA values for the fan "OFF" period are shown in Table 1. Power consumption data (P) as a function of the area difference (ΔA) were plotted as shown in Fig. 7. An empirical relation between P and ΔA for the fan "OFF" period was determined as:

$$P = 0.026\Delta A + 0.957 \tag{1}$$

using linear regression analysis. The equation and the residual R^2 value are also shown in Fig. 7. The scatter in the data is attributed to the variability in the weather data and the uncertainties in the instrumentation and power meter readings.

The above empirical equation is applied to the measured fan "OFF" period temperature data of winter 2002 to see how it compares. The inside operating conditions of the THH during winter 2002 was similar to that of winter 2009. (Unfortunately, the daily/hourly power consumption and temperature data for the period 2003–2008 were not available; the focus of THH research was different at that time.) The measured indoor and outdoor temperature profiles for 6 days in winter 2002, with fan "OFF" condition, are as shown in Figs. 8a and 8b, respectively. The area difference (ΔA) values were easily computed from these indoor–outdoor temperature profiles. A systematic daily/hourly power consumption data was not recorded; only an average power consumption value of 12 kW h/day was reported [14]. Hence, power consumption versus ΔA relationship could not be established for that period. However, an attempt is made here to compare the power consumption values for the two winter seasons assuming that the empirical relation obtained for the winter 2009 holds good for the winter 2002 also. When used with the ΔA data of winter 2002 (fan "OFF" condition), Eq. (1) gives an average power consumption value of 13.58 kW h/day (as shown in Table 2) compared to 12 kW h/day mentioned above, a difference of 1.58 kW h/day. This shows that for the fan "OFF" period, there is only a small difference in the average power consumption values for winter 2002, which indicates that the empirical relation obtained for winter 2009 is still valid for winter 2002. This also reveals that the thermal behavior of the THH building has not changed significantly over a 7-year period.

7.2. Power consumption with mechanically-induced fresh-air ventilation (fan "ON" period)

The data recorded during this period were similar to those during the fan "OFF" period except that the fresh-air ventilation

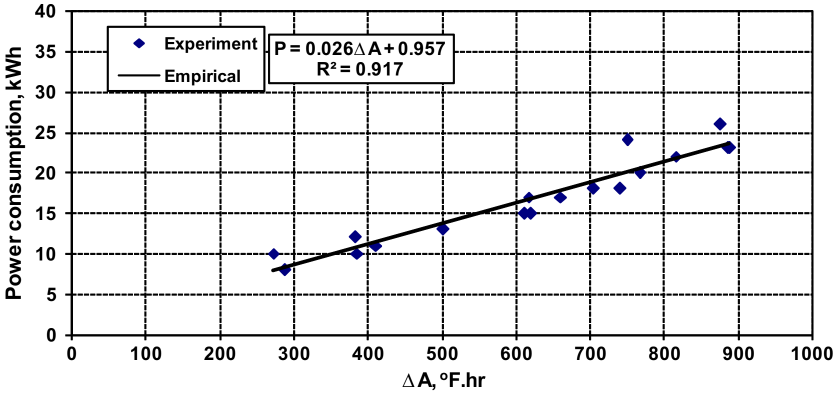

Fig. 7. Plot showing power consumption versus ΔA relation for the fan "OFF" period of winter 2009.

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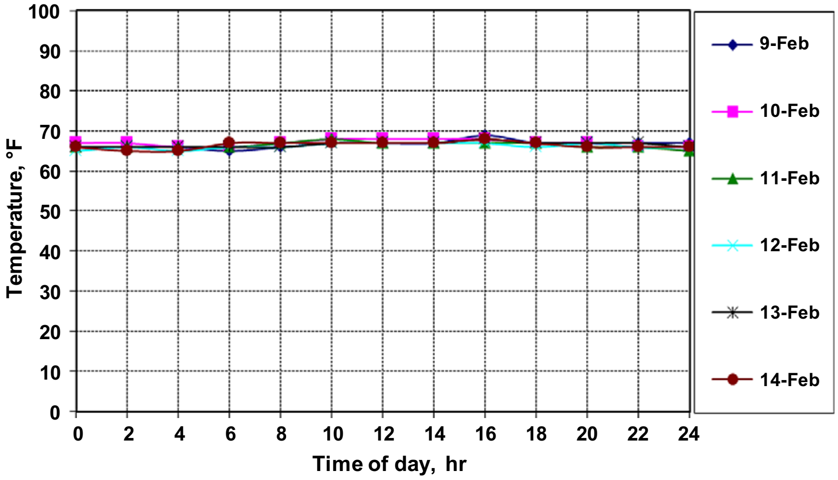

Fig. 8a. Indoor temperature profiles for the fan "OFF" period of winter 2002.

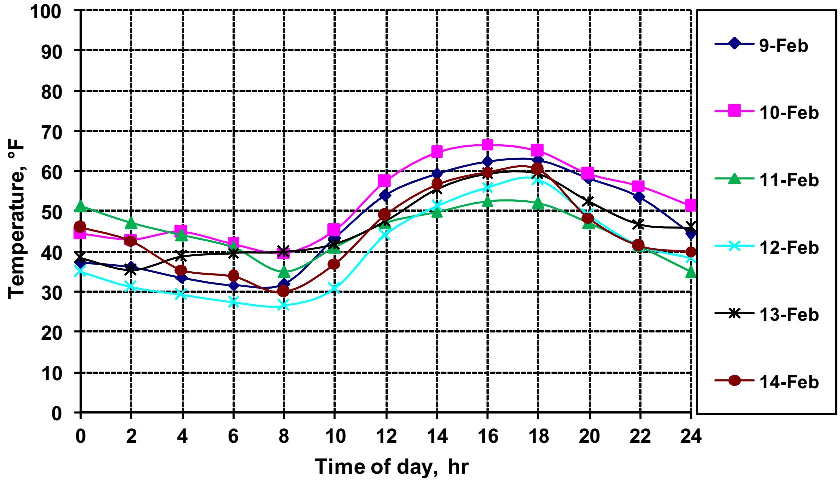

Fig. 8b. Outdoor temperature profiles for the fan "OFF" period of winter 2002.

Table 2
Estimated power consumption values for the fan "OFF" period of winter 2002 using Eq. (1).

Data no.	Time duration (h)	Area diff. ΔA (°F h)	Power consumption (kW h) (using Eq. (1))
1	24	468.14	12.89
2	24	347.26	9.81
3	24	517.24	14.15
4	24	630.22	17.03
5	24	484.24	13.31
6	24	522.90	14.29
			Average = 13.58 kW h

fan was running at 60 cfm (28.3 L/s) throughout the test period. The indoor–outdoor temperature data were obtained for a period of 12 days during the winter months (January–March) of 2009. The indoor and outdoor temperature profiles are as shown in Figs. 9a and 9b, respectively. The area difference (ΔA) values were computed from these temperature profiles in a similar manner described above for the fan "OFF" case. The time duration, power consumption and the corresponding ΔA values for the fan "ON" period are shown in Table 3. The power consumption (P) data as a function of area difference (ΔA) were plotted and an empirical relation between P and ΔA for the fan "ON" period was determined as:

$$P = 0.030\Delta A + 4.775 \qquad (2)$$

using linear regression analysis, as shown in Fig. 10. The residual R^2 value is also shown in the figure. (Note: The data point number 4 in Table 3 is not displayed in Fig. 10 because the x-scale is kept the same as in Fig. 7 for easy comparison; however that data point was included in the analysis for establishing the empirical relation given here.) The scatter in the data, again, is attributed to the variability in the weather data and the uncertainties in the instrumentation and power meter readings.

Empirical Eq. (2) is applied to the measured fan "ON" period temperature data of winter 2002 to see if it is valid. The inside operating conditions of the THH during winter 2002 was similar to that of winter 2009. The measured indoor and outdoor temperature profiles of 6 days in winter 2002 (fan "ON" period) are as shown in Figs. 11a and 11b, respectively. Again, a systematic daily/hourly power consumption data was not available for that period; only an average power consumption value of 15.29 kW h/day was reported [14]. When used with the ΔA data of winter 2002 (fan "ON" period), Eq. (2) gives an average power consumption value of 16.09 kW h/day (as shown in Table 4) compared to

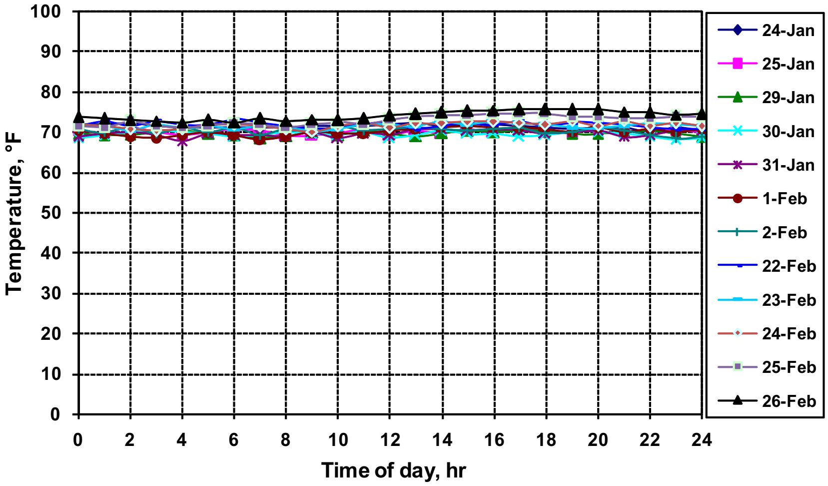

Fig. 9a. Indoor temperature profiles for the fan "ON" period of winter 2009.

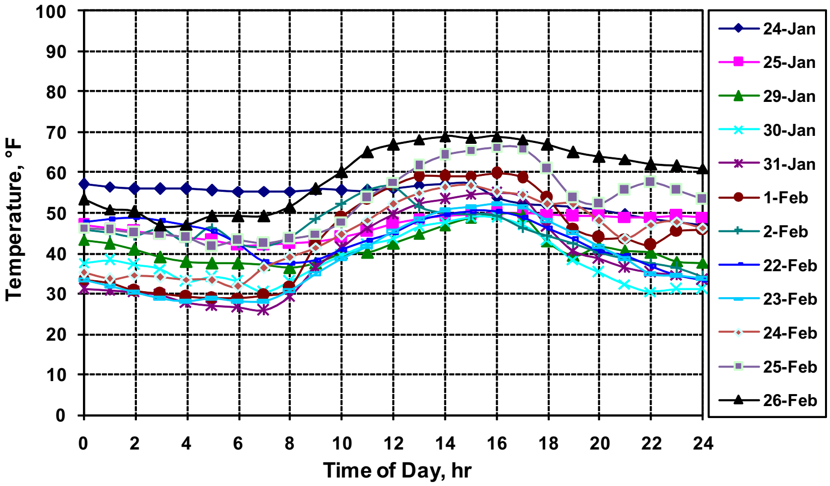

Fig. 9b. Outdoor temperature profiles for the fan "ON" period of winter 2009.

Table 3
Measured power consumption and ΔA data for the fan "ON" period of winter 2009.

Data no.	Time duration (h)	Area diff. ΔA (°F h)	Power consumption (kW h)
1	24	604.06	23
2	24	713.94	29
3	7	174.90	17
4	65	1846.73	59
5	24	739.70	28
6	24	704.63	28
7	18	580.79	23
8	24	569.09	21
9	24	542.64	19
10	18	443.40	16
11	24	441.71	14
12	24	396.27	14
13	24	272.15	11
14	24	281.02	11

15.29 kW h/day, a difference of 0.80 kW h/day. This shows that, similar to the fan "OFF" case, there is no appreciable change in the power consumption values of winter 2002 and winter 2009. Thus, both fan "OFF" and fan "ON" results reveal that the thermal performance of the THH building in the winter season has not changed significantly over a 7-year period.

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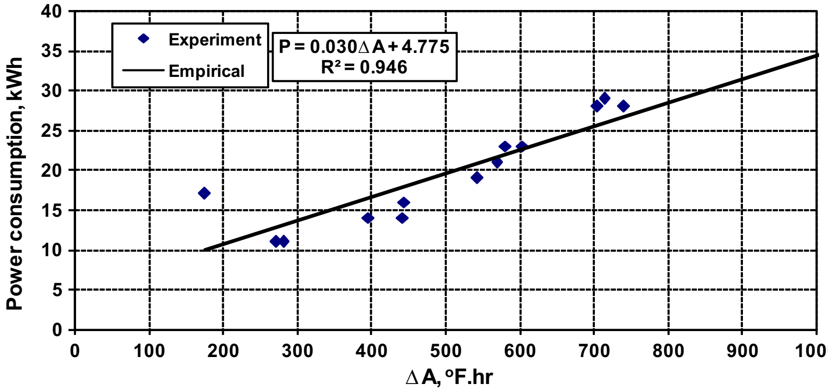

Fig. 10. Plot showing power consumption versus ΔA relation for the fan “ON” period of winter 2009.

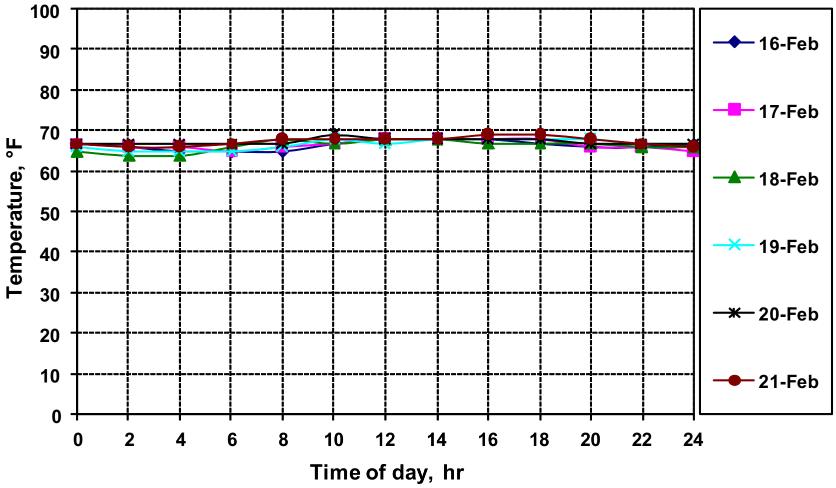

Fig. 11a. Indoor temperature profiles for the fan “ON” period of winter 2002.

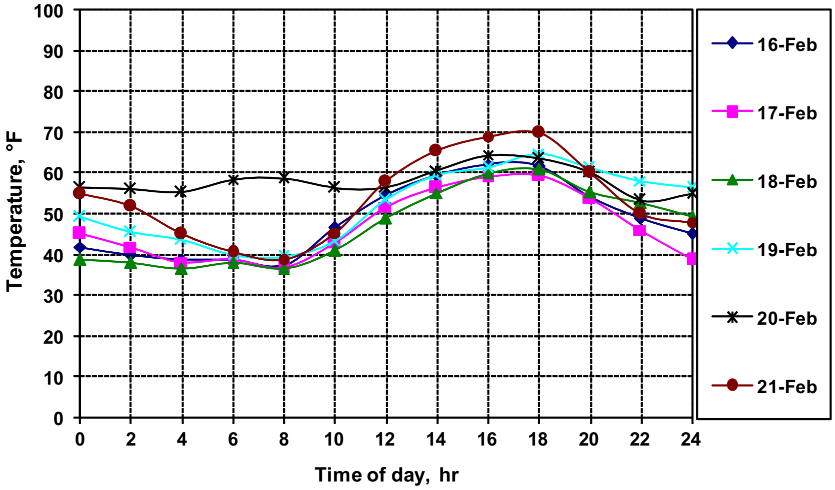

Fig. 11b. Outdoor temperature profiles for the fan “ON” period of winter 2002.

8. Conclusions

Experiments, using the Tuskegee Healthy House as a test building, were conducted to determine how the power consumption of a small residential building envelope varies as a function of the variations in the inside and outside weather condition. Measurements were made during winter 2009 with and without the mechanically-induced fresh-air ventilation, i.e. using fan “ON” and fan “OFF” condition, respectively. A simple methodology is introduced to obtain an empirical relation between building power consump-

Table 4
Estimated power consumption values for the fan "ON" period of winter 2002 using Eq. (2).

Data no.	Time duration (h)	Area diff. ΔA (°F h)	Power consumption (kW h) (using Eq. (2))
1	24	428.94	17.47
2	24	471.10	18.72
3	24	466.82	18.59
4	24	362.68	15.51
5	24	227.40	11.51
6	24	335.86	14.72
			Average = 16.09 kW h

tion and indoor–outdoor temperature profile area differences. It was assumed that the heat pump controls only the indoor temperature and not the indoor relative humidity and hence, only temperature variations were considered in the analysis. Effects due to occupants, air/moisture leakage, and material deterioration were not considered. Empirical equations for the building power consumption were obtained from the measured temperature data of winter 2009 for both fan "OFF" and fan "ON" conditions as: $P = 0.026\ \Delta A + 0.957$ and $P = 0.030\ \Delta A + 4.775$, respectively. These equations were applied to the measured temperature and power data of winter 2002 to compare and evaluate the thermal performance of the THH. The equations agree favorably with the winter 2002 data indicating that there is no appreciable difference in power consumption values during the winter season of 2002 and 2009 which, in turn, reveals that there is no significant change in the thermal performance of the THH over a 7-year period. Thus, the methodology presented in this work can be utilized as a means to compare and evaluate the thermal performance (or deterioration) of a given building envelope from season to season and between the same seasons in different years, in addition to the routine building inspection for structural damage/degradation from time to time.

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