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A QUICKER METHOD FOR DETERMINING THE UA-VALUE OF A RESIDENTIAL BUILDING

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ABSTRACT

The present study on determining the UA-value of a residential building is based on a simple heat-balance approach. It is quicker than any traditional long-term in-situ measurement method. The supply and return air temperatures, the relative humidity of the heating and cooling system, and the outdoor ambient temperature were measured overnight, allowing the UA-value to be calculated from the system's on and off time periods.

In addition to temperature loggers, two HFP01 heat-flux plates by HukseFlux® and two HFS-3 thin-film heat-flux sensors by Omega® were employed in this study. Both sensors were calibrated using commercially available polystyrene insulation sheathings with R-values of 1, 3, 5, 10, 15, and 20 hr-ft^2-°F/Btu as standard references.

The total UA-value was found to be 830 ± 10 Btu/hour-°F (or a thermal index of 6.1 ± 0.1 Btu/ft^2-°F-day) by using the heat-balance method for this 3,290 ± 5 ft^2 house located at latitude 38°N and longitude 78°W, inland of Zone 4. This value was then compared to the in-situ measured UA-value of 800 ± 10 Btu/hour-°F and a retracted UA-value of 840 ± 20 Btu/hour-°F based on the house's 10-year average electricity consumption data, known as the Degree-Day Method.

INTRODUCTION

The energy use per household in the United States in the past 35 years is down about 10% (Nadel et al. 2015) even though homes are larger and contain many more energy-using devices. This improvement can be attributed to more energy efficient appliances, lighting, heating and cooling equipment, and reducing heat loss through building envelope components.

One of the most important factors in improving building efficiency is to lower the transmittance of the building envelope: the so-called U-factor or U-value. However, it is not easy to obtain such a value. Most home owners don't have thermal property information such as the R-value of a composite wall of their house, and detailed information about the structure of the house envelope components. In-situ measurement of these values is possible but requires a lengthy effort to collect the data. Analyzing the data could be complicated and uncertain.

A newly invented heat-loss measuring device called a U-value meter was utilized in a Danish project (Sorensen 2013). The advantage of using this U-value meter is a surprisingly short data collection time. The inventor of the device claimed that a single U-value test can be done in 20 seconds. However, the device might be expensive and using "U-value meter" as the name of the equipment might not be as practical as "R-value meter" given that the heat transfer coefficients of the inside and outside convective layers of the building envelope depend on both the indoor air temperature and outdoor weather conditions.

In 2013, a new approach based on infrared thermography (IRT) was developed for in-situ measurements (Nardi et al. 2013). The advantages of this new approach are its non-invasiveness and the possibility of inspecting relatively large areas in real time. Their results show a more accurate transmittance estimation. However, certain conditions must be fulfilled. For example the surface temperature of the wall should be greater than the outdoor environment temperature by at least 2°C and the difference between the indoor environment temperature and the outdoor environment temperature should be great. Also, the measurement of the spectral emissivity should be accurate and the weather conditions should be stable.

For these reasons, a quicker yet still accurate heat-balance method of obtaining the total UA-value of a residential building was developed in the current study.

THE HEAT-BALANCE METHOD

The heat-balance method is based on the principle of conservation of energy: the heat loss through the building envelope during a period of time is equal to the heat supplied to the house.

Data were collected for five consecutive days from 13 to 17 December 2017. Figure 1 shows two typical days of heat pump return and supply temperature profiles together with outdoor ambient temperature. Data from 13 December 2017 are shown on the top part of Figure 1 and data from 16 December 2017 are shown on the bottom. The heat pump ON-cycles were long since it was dry and cold outside on December 13. The ON-cycles of the heat pump were not as long on the morning of December 16 because the outside air had high humidity and the temperature was right below freezing, which trigged several defrost cycles.

The thermostat of the heat pump was set at 70°F during those five days which can be clearly seen from the return air profiles in Figure 1. The heat-balance equation used in obtaining the total UA-value of the house can be written as Equation (1) below.

$$UA = \frac{\rho \dot{V}\left(h_{Supply} - h_{Return}\right)t_{ON} + Q_{Int}}{\left(T_{Indoor} - T_{Outdoor}\right)\left(t_{ON} + t_{OFF}\right)} \tag{1}$$

Here, hs are the air enthalpies in Btu/lbm, ts are times in hours, Q_{Int} is the total internal heat gain in Btus, and Ts are temperatures in °F.

Measuring the Total UA-value

In addition to collecting the On- and OFF-cycle history of the heat pump, the average volumetric flow rate of the air at the outlet of the indoor coil of the heat pump was measured as 1,170 cfm ± 10 cfm using a hot-wire anemometer. The relative humidity of both supply and return air to the heat pump, and outdoor air temperature were also recorded using three temperature and humidity loggers from midnight to 6 a.m. when there was no radiant heat from the Sun, and activities in the house were minimum. Thus the least and almost constant rate of internal heat gain can be easily estimated. A power meter was employed to measure the power consumption rate of a refrigerator in the kitchen (0.320 kWh in six hours, or 53 W of electric power constantly extracted from the wall socket into the house as heat), two standby power strips (1.0 W each), two standby ovens (1.5 W each), seven digital clocks (1.4 W each), one standby power strip for an entertainment console including a cable box and an internet router (20 W), and two occupants (60 W each). The total was 210 W, that is, about 1.26 kWh or 4,300 Btu of internal heat gain (in addition to the heat supplied by the heat pump) contributed to the house during the entire six-hour data collection period.

Heat pump ON- and OFF-cycle times were counted by hovering the computer mouse over each of the ON- and OFF-cycle profiles on the spreadsheet as shown in Figure 1 and Table 1.

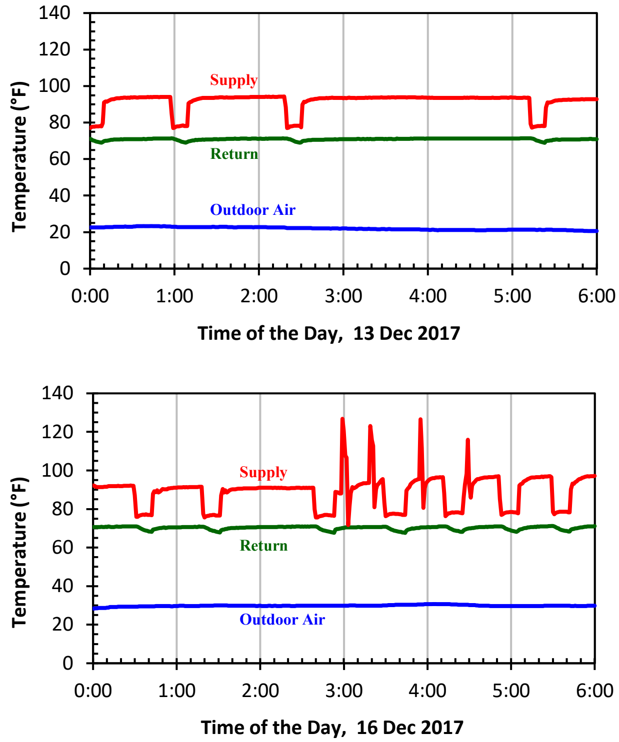

Figure 1 *Six-hour temperature profiles of the heat pump return and supply air and outdoor ambient air. Data were taken on 12/13/17 (top) and 12/16/17.*

The properties of air including its average density and enthalpy differences across the heat pump indoor unit were calculated using EES® (Engineering Equation Solver by f-chart®) as shown in Figure 2 (it is a screen shot of a typical data reduction process). The enthalpy difference between the heat pump supply and the return air using EES® Parametric Table was calculated minute by minute. The input data were the dry-bulb temperature and relative humidity (normally around 50% and 35% for heat pump return and supply air, respectively). The output was the net heat supply to the house during the heat pump ON-cycle period, which then divided by the measured temperature difference between the indoor and outdoor ambient temperatures throughout the entire six-hour period to obtain the UA-value as described in Equation (1). The five-day average total UA-value of the house was calculated as 830 Btu/hour-°F ± 7 Btu/hour-°F as shown in Table 1.

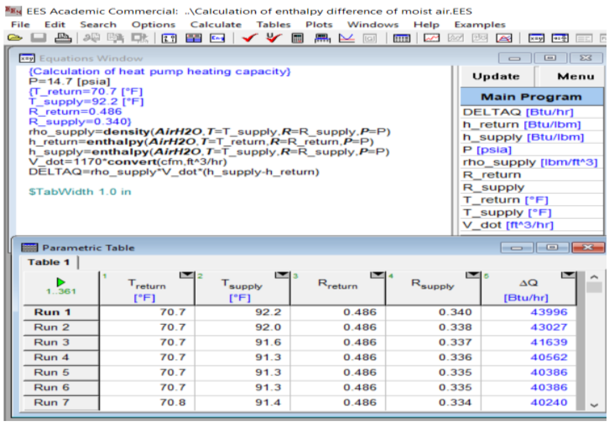

Figure 2 *A minute-by-minute calculation of enthalpy difference between heat pump supply and return air using EES® Parametric Table for all six hours (only the first seven minutes are shown here) of data in the heat-balance method.*

It is worth noting that if the thermostat is set lower than 70°F, the total UA-value of the house calculated by the heat-balance method will be lower because the inner convective heat transfer coefficient will be lower which in turn will make the overall U-value lower. See Equation (2).

$$\frac{1}{U} = \frac{1}{h_i} + \sum_{j=1}^{N} \left(\frac{t}{k}\right)_j + \frac{1}{h_o} \tag{2}$$

Here, h_i and h_o are the heat transfer coefficients of the inner and outer convection layers, respectively, t is the thickness, and k is the thermal conductivity of each layer of the composite building envelope component.

Table 1 *Five consecutive days of calculated UA-values using the heat-balance method.*

Date	**12/13/17**	**12/14/17**	**12/15/17**	**12/16/17**	**12/17/17**
Heat Pump Cycle ON Time, t_{ON} (hours)	5.28	3.28	3.73	4.37	3.30
Heat Pump Cycle OFF Time, t_{OFF} (hours)	0.72	2.72	2.27	1.63	2.70
ON Time Average, $\Delta\dot{Q} = \rho\dot{V}\Delta h$ (Btu/hour)	44,226	55,879	53,703	45,068	61,846
Internal Heat Gain, Q_{Int} (Btu)	4,300	4,300	4,300	4,300	4,300
Average Outdoor Air, T_{Out} (°F)	22.0	32.8	28.6	29.8	28.6
Average Indoor Air, T_{In} (°F)	70.9	70.1	69.3	70.2	70.4
Auxiliary Heat, (Yes/No)	No	No	Yes	Yes	Yes
Total **UA-value** of the House, (Btu/hour-°F)	811 ± 16	840 ± 16	838 ± 15	830 ± 16	831 ± 13

COMPARISONS

1. The In-situ Measurement of UA-value

For comparison, the U-value was measured conventionally in the current study. To ensure the accuracy of measuring the R-value of the building envelope materials it was essential to calibrate the heat-flux sensors used in the study. Room air conditions were kept at 70°F and 50% relative humidity at all time during the calibration period and the settling time of each of the four heat-flux sensors was recorded for later reference.

Calibration of heat flux sensors

The requirements for calibrating heat-flux sensors include the following: (1) the R-values of the reference specimens have to be from a recognized national standard laboratory, (2) Fourier's law of heat conduction must be used to calculate the thermal resistance of the building envelope materials, (3) a proper layer of insulation for the edges of the reference specimen is needed to ensure a one-dimensional heat transfer, and (4) an infrared camera is also needed to check the uniformity of the reference specimen during the calibration.

Commercially available polystyrene foam boards with rated R-values of 1, 3, 5, 10, 15, and 20 hour-ft^2-°F/Btu were used in calibrating two types of heat-flux sensors in this study. The calibration apparatus consists of a foam board that can be fitted into a 55-in high and 20.5-in wide window panel cavity as shown in Figure 3, two HFP-01 heat-flux plates from Hukseflux®, two HFS-3 heat-flux sensors from Omega®, four thermocouple wires, and a OM-DAQPRO-5300 data logger from Omega® with a 16-bit sampling resolution for 0 to 50 mV output range.

Figure 3 FOAMULAR® polystyrene insulation sheathiongs were used for calibrating all four heat-flux sensors. Each specimen was cut to fit into an existing window panel.

The ASTM International (American Section of the International Association for Testing Materials) Practices (ASTM C 518-10, C 1046-95, C 1155-95 2013) were followed very closely in collecting and generating calibration curves. Figure 4 shows the calibration curves of the four heat-flux sensors used in this study. The two Hukseflux® heat-flux plates have higher sensitivity (on the order of 200 µV per Btu/hour-ft^2-°F) than the two Omega® thin-film heat-flux sensors (on the order of 5 µV per Btu/hour-ft^2-°F). Thus, the two Omega® sensors were used only for measuring low R-value components such as windows and doors.

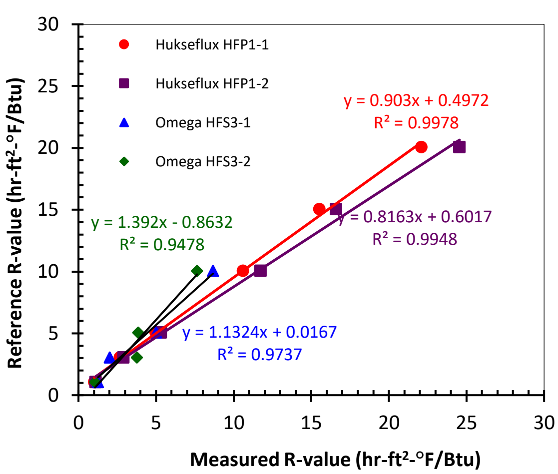

Figure 4 Calibration curves of two Omega® HFS3 thin-film heat-flux sensors and two Hukseflux® HFP1 heat-flux plates.

The combined uncertainty of the measured R-value of each component of the building envelope was calculated from the standard uncertainty analysis procedures using the following equation.

$$U_Y = \sqrt{\sum_i \left(\frac{\partial Y}{\partial X_i} U_{X_i} \right)^2} \tag{3}$$

Here, Y is the dependent variable, X_i are the independent variables, and U_Y and U_{X_i} are their corresponding uncertainties.

Measuring the U-factors

For windows and glass doors, two Hukseflux® heat-flux plates were used: one was placed at the COG (center-of-glass), one was mounted on the EOG (edge-of-glass), and one Omega® HFS-3 thin-film heat-flux sensor was placed along the frame of the window or door. The effects of COG, EOG (a 2.5-in strip around the inner edges of the frame), and frame were considered to properly calculate the total UA-value of each glass door and window.

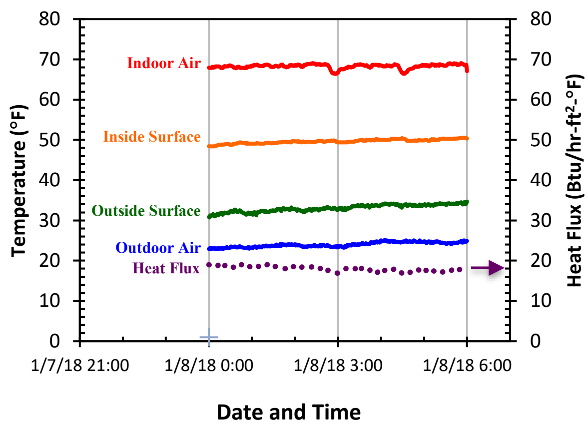

Figure 5 A typical U-value measurement (front glass-door of the house) period from midnight to 6:00 a.m.

Most data were collected in a 12-hour period in the winter. However, only data from the six hours from midnight to 6:00 a.m. were analyzed (as shown in Figure 5) so that the internal heat gain of the house would be mostly from the refrigerator condenser in the kitchen, which won't cause any substantial thermal mass effect to the test sections. All the U-factors were calculated based on Fourier's law of conduction as listed below in Equation (4). Note that the U-factor was calculated as the ratio of the summation of six hours of heat flux to the summation of six hours of temperature differences. Thus a steady-state condition was not necessary.

$$U = \frac{\sum_{j=1}^{361} \dot{q}_j}{\sum_{j=1}^{361} \left(T_{ij} - T_{oj} \right)} \tag{4}$$

Here, $\dot{q}_j$ is the minute average of heat flux in Btu/hour-ft^2. Note that during the test period, all the venetian blinds on windows were down, and the drapes on the sunroom French door were drawn, which made the measured U-factors much lower than the code values.

For walls in both the first floor and the basement, a stud finder was used to locate the frame of walls and two Hukseflux® heat-flux plates were used: one for measuring the U-factor of the frame and the other for measuring the U-factor of the cavity with insulation.

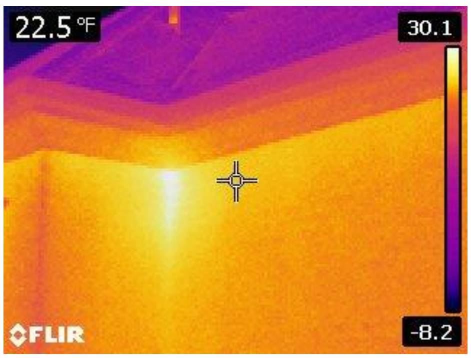

Figure 6 *Thermal image showing more heat loss through the corner of a wall.*

Since the walls were constructed with 2” by 4” studs and 16” off-center spacing, a 15% wall area of studs and an 85% wall area of cavities with insulation was used to calculate the measured average U-factor to be 0.0541 ± 0.0001 Btu/hour-ft^2-°F.

It is worth noting that wall corners have a higher U-factor than the rest of the wall because the presence of a thermal bridge. The temperature contrast of such a difference can be seen clearly from the thermal image shown in Figure 6.

For the basement walls, two Hukseflux® heat-flux sensors were mounted inside the finished basement wall on the open-air side. The U-factor was measured to be 0.0568 ± 0.0002 Btu/hour-ft^2-°F. The U-factor of the floor above the crawl space was measured to be 0.0338 ± 0.0005 Btu/hour-ft^2-°F.

It is harder to measure the U-factor of the sloped roof. One Hukseflux® heat-flux sensor was taped to the interior side of the ceiling, and another was mounted on the upper side of the ceiling in the attic. Another Hukseflux® heat-flux sensor was taped to the inner side of the roof. With the aid of measured corresponding temperatures, the U-factor for ceiling, attic, and roof combined was measured to be 0.0309 ± 0.0001 Btu/hour-ft^2-°F. Note that the blown-in cellulose in the attic is uneven, thus the measured U-factor of the sloped roof possesses a higher degree of uncertainty than any other envelope components in the house.

Tabulating all the measured UA-values

The total UA-value of the house then is the sum of the UA-value of each of the building envelope component. Note that dimensions of each part of the house (as seen in Figure 7) were measured carefully to ensure the accuracy of getting this total UA-value.

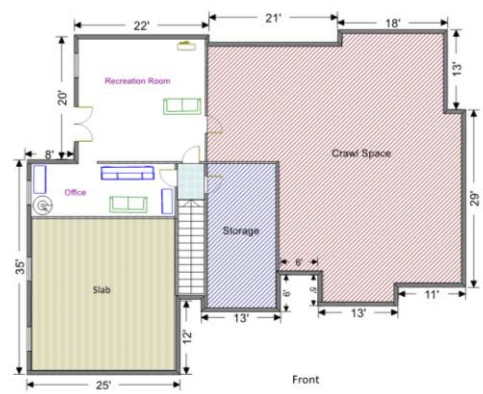

Figure 7 *Floor plan of the basement of the house with dimensions depicted along the outline of the house.*

The total UA-value of the house was measured to be 804.1 ± 9.8 Btu/hour-°F as shown in Table 3. Note that the heat loss due to ventilation was calculated based on an air-change rate (ach) of 0.52 ± 0.2, that is, an air volume 0.52 times the volume of the house was vented per hour. This ach value was calculated based on a natural infiltration rate of 20 from a blower-door test of CFM50 equal to 4,600 ± 100 cfm. It is worth noting that the standard ventilation requirements for the kitchen and bathrooms were checked according to the ASHRAE Standard 62.2 for Existing Buildings (2013).

For comparison, the U-factors for residential building envelope components per local construction code (Virginia building code 2018) are listed in parentheses alongside the in-situ measured U-values in Table 2 below.

The process of in-situ measurement of U-factors is tedious and often involves a large uncertainty caused by the thermal bridges at window sills and wall corners. The data reduction might require a lengthy summation technique to assure a converged U-factor.

Table 2 Comparison of the UA-value between the in-situ measured (top) and local code (Climate Zone 4 except Marine) values.

Envelope Component	Area (ft^2)	U-factor (Code) ± Uncertainty (Btu/hour-ft^2-°F)	UA-value (Code) ± Uncertainty (Btu/hour-°F)
First Floor			
Ceiling, Attic, and Roof	2,601 ± 5	0.0309 (0.030) ± 0.0001	80.4 (78.0) ± 0.3
Door to the Garage	22.8 ± 0.2	0.0734 (0.100) ± 0.0003	1.7 (2.3) ± 0.02
Floor above the Crawl Space	1,823 ± 5	0.0338 (0.047) ± 0.0005	61.6 (85.7) ± 0.9
Front Glass Door	64.5 ± 0.4	0.2282 (0.350) ± 0.0003	18.2 (22.6) ± 0.1
Inner Garage Wall	242 ± 3	0.0547 (0.059) ± 0.0001	13.2 (14.3) ± 0.2
Sunroom French Doors*	121 ± 1	0.2439 (0.300) ± 0.0003	29.5 (36.3) ± 0.2
Walls	1,389 ± 4	0.0541 (0.082) ± 0.0001	75.1 (113.9) ± 0.3
Windows*	439 ± 2	0.2689 (0.300) ± 0.0007	118.0 (131.7) ± 0.6
Subtotal			397.8 (484.7) ± 1.2
Basement			
Crawl Space Wall	390 ± 2	0.0821 (0.065) ± 0.0012	32.0 (25.4) ± 0.5
Door to the Crawl Space	21.7 ± 0.2	0.1441 (0.100) ± 0.0037	3.1 (2.2) ± 0.1
Doors to the Garage	43.9 ± 0.2	0.0621 (0.100) ± 0.0003	2.7 (4.4) ± 0.02
Concrete Slab Floor with Carpet	690 ± 2	0.1408 (0.100) ± 0.0023	97.2 (69.0) ± 1.6
Outside Glass Door	38.7 ± 0.3	0.1739 (0.350) ± 0.0004	6.7 (13.5) ± 0.1
Outside Wall	173 ± 2	0.0568 (0.082) ± 0.0002	9.8 (14.2) ± 0.1
Windows	26.2 ± 0.2	0.2392 (0.350) ± 0.0003	6.3 (9.2) ± 0.05
Subtotal			157.8 (137.8) ± 1.7
Ventilation Heat Loss			
cfm50	4,600 ft^3/min		
Total Air Volume of the House	26,328 ft^3		
Air change Rate (ach)	0.52 per hour		
Subtotal			248.4 (248.4) ± 9.6
Total UA-Value			**804.1** (871.0) ± **9.8**
Total Floor Area	3,291 ft^2		
Thermal Index	5.9 (6.4) Btu/°F per ft^2 of total floor area		
Total Surface Area	5,431 ft^2		
Weighted UA-Value	0.15 (0.16) Btu/hour-°F per ft^2 of total surface area		

*During the test period, drapes on sunroom French doors were drawn and venetian blinds on all the windows were down.

2. The Degree-Day Method

Also for comparison, the Degree-Day Method for estimating the total UA-value of buildings demonstrated by Kissock (2012) was adopted in the current study. The total UA-value of the house can be extracted from its actual energy-use data. The procedure of getting it is described in the following five steps.

(1) Estimate the baseload of the house:

Obtain 10 years of electricity bills that contain monthly electrical energy consumption in kWh from the home owner; plot them against the corresponding local heating degree days (HDD) as shown in Figure 8. The intercept of the linear trendline of such a graph

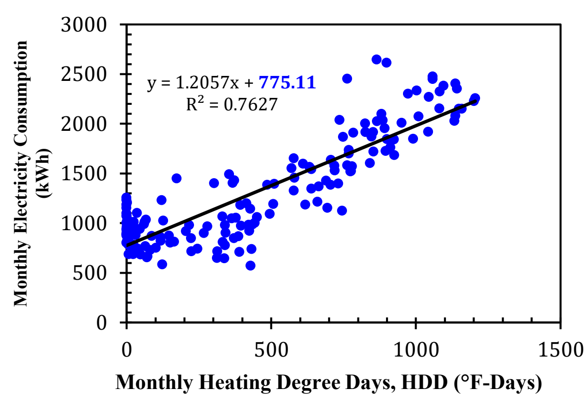

Figure 8 *The baseload of the house is 780 kWh ± 30 kWh per month which is the intercept of this monthly electricity consumption versus monthly heating degree-days linear trendline.*

represents the baseload of the house. It is 780 kWh ± 30 kWh per month. This is the total electrical energy used for hot water, lighting, and cooking among other basic needs for the house.

(2) Calculate the amount of heat supplied to the house for a selected month of the year:

Subtracting the baseload from the monthly average electricity consumption of 1,990 kWh leaves 1,210 kWh per month of electrical energy for the space heating for the month of December. With a 4.0 heating COP (coefficient of performance) of the heat pump, a total of 4,840 kWh (or 16.5×10^6 Btu, or 16.5 MMBtu) of heat will be delivered to the house for the entire month of December.

(3) Calculate the balanced air temperature in the house:

The internal heat gain of the house was estimated to be 6,000 Btu/hour, which includes the radiant heat from the occupants of the house; solar heat gain through the fenestrations; and radiant heat from lighting, cooking, and electronic devices, for example. With this internal heat gain, the balanced air temperature of the house can be calculated as 62.5°F by subtracting the ratio of internal heat gain of 6,000 Btu/hour to an initially guessed UA-value (say 800 Btu/hour-°F) from an indoor air setting temperature of 70°F.

(4) Calculate the balanced heating degree days:

Take the balanced air temperature of 62.5°F and plug it into the empirical expression proposed by Randolph and Masters (2008) as shown in Equation (5) to interpolate the annual HDD65 (HDD based on 65°F reference temperature) of 5,200 °F-days [(from 30 years, 1/1/1988 to 12/31/2017 average monthly HDD65 data from the weather station in Dale Enterprise, Virginia (NOAA online weather data 2018)] to the balanced HDD(Tb) of 4,642 °F-days. Note that the correlation listed in Equation (5) was validated in the current study to be within ±1% compared to the actual local weather data using both simple Average Method and Min and Max Method (also known as McVicker (1946) Formulas). Then, the degree-days become 803 °F-days for the month of December alone: a 17.3% of the annual balanced HDD(Tb) based on the 30-year-average portion of the HDD(Tb) that falls in December.

$$\boldsymbol{HDD}\left(\boldsymbol{Tb}\right) = \boldsymbol{HDD}65 - \left[0.021\boldsymbol{HDD}65 + 114\right]\left(65 - \boldsymbol{T_b}\right) \quad (5)$$

(5) Calculate the UA-value of the house:

Divide the amount of heat supplied to the house of 16.5×10^6 Btu (from Step 2) by the local balanced heating degree days of 803 °F-days (or 19,274 °F-hours) for the month of December from Step (4). One can calculate the UA-value of the house to be 856 Btu/hour-°F; an iteration then will be needed to steps from (3) to (5) until the UA-value is converged to 840 ± 20 Btu/hour-°F.

The degree-day method seems quite straightforward in calculating the UA-value of a house if an iterative computing tool is available; however, most of the utility companies would allow their customers to access only 18 months of usage history not long enough to generalize a usage pattern. The estimation of the baseload of the house, the internal heat gain, and the balanced HDD(Tb) all would greatly affect the accuracy of the calculated UA-value.

CONCLUSION

The simple heat-balance method for determining the total UA-value of a house can serve to quickly estimate the heat transmitted into or out of the building. The accuracy is proven to be relatively good. It only requires a hot-wire anemometer to measure the volumetric flow rate, temperature and relative humidity loggers to measure both temperature and relative humidity of heat pump return, and supply air and outdoor ambient conditions.

By using the heat-balance method, the total UA-value was measured to be 830 ± 7 Btu/hour-°F (or thermal index of 6.1 ± 0.1 Btu/ft^2-°F-day per ft^2 floor area, or weighted UA-value of 0.16 ± 0.01 Btu/ft^2-°F-day per ft^2 wall area) for this 3,290 ± 5 ft^2 house located at latitude 38°N and logitude 78°W in inland climate Zone 4. This value was then compared to two other UA-values: one from the in-situ measured UA-value of 804.1 ± 9.8 (or 810 ± 10) Btu/hour-°F, another from the retracted UA-value of 840 ± 20 Btu/hour-°F based on the house's 10-year average energy consumption data. All three UA-values fall into a range of 830 ± 30 Btu/hour-°F.

Note that the heat-balance method can be used for buildings with different sources of energy for heating and cooling as long as the net amount of energy supplied to or extracted from the building is known.

ACKNOWLEDGMENT

The author would like to thank Dr. Eric Maslen, the former department chair of Integrated Science and Technology at James Madison University for his encouragement and financial support in obtaining all the needed equipment for this project.

NOMENCLATURE

A = the surface area of the building envelope component in ft^2.

h_i = the inside heat transfer coefficient in Btu/hour-ft^2-°F.

h_o = the outside heat transfer coefficient in Btu/hour-ft^2-°F.

h_{Return} = the specific enthalpy of air returns from the ducts in Btu/lbm.

h_{Supply} = the specific enthalpy of air supplies to the building via the ducts in Btu/lbm.

ρ = the density of the air in lbm/ft^3.

$\dot{q}$ = the heat flux through the envelope in Btu/hour-ft^2.

$\Delta\dot{Q}$ = the specific enthalpy difference in Btu/hour.

Q_{Int} = the internal heat gain of the building throughout the entire ON and OFF period in Btu.

t_{OFF} = the heat pump OFF-cycle time in hours.

t_{ON} = the heat pump ON-cycle time in hours.

T_{Indoor} = the average indoor air temperature in °F.

$T_{Outdoor}$ = the average outdoor air temperature in °F.

U = the U-factor of the building component in Btu/hour-ft^2-°F.

UA = the UA-value of the building in Btu/hour-°F.

$\dot{V}$ = the volumetric flow rate of the air in ft^3/hour.

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