

Measurement and Detailed Analysis of Indoor and Outdoor Environment Conditions and Energy Consumption of a Single Family Residence

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Building energy simulation model needs to be calibrated using measured data, so different energy efficient features can be evaluated precisely by well-calibrated simulation model. This paper discusses procedures for measuring and analyzing data from the case-study house to provide reliable data for the calibration of the building energy simulation model. It also includes the detailed analysis of duct heat loss/gain in the attic space of the case-study house. Several sensors were installed to measure the attic temperature, outdoor temperature, indoor temperature, duct supply temperature, diffuser temperature, inside roof deck temperature in the attic space, natural gas, and the air-conditioner electricity use at the case-study house for one year. Graphical and statistical analysis was performed to identify the factors that statistically influence a cooling energy use. It was found that as supply air moves through duct system in the attic space during the summer, average air temperature increment from the air condition to the diffuser was 3.2 ºF and maximum temperature increment was 9.8 ºF. It was also found that attic air temperature was the most significant factor affecting the cooling energy use.

Keywords: Environment Condition, Data Measurement, Duct Heat Loss/Gain, Residential Building, Energy Efficiency

Introduction

Building energy simulation model is a computer model that can project building energy consumption based on the building design, materials, HVAC systems, etc. In the energy simulation model, the calibration procedure with actual data has been considered as critical procedure to provide the validity of the model for future applications of the possible energy efficient features. Therefore, well-calibrated energy simulation models play a major role in the measurement of the retrofit savings of the building since they can be used to calculate the energy savings for specific combinations of retrofits by building a virtual replica of a building. As a preliminary and significant stage to develop the well-calibrated simulation model, the accurate data measurement, collection, and analysis from the case-study building are critical.

It also has been known for a long time that the attic space between the roof and the ceiling of a building is responsible for a substantial portion of heat transfer, and leaky ducts in the attic space are the major cause of excessive energy use in hot and humid climate region. Around 35% of single-family residences in U.S. have the duct systems that pass through unconditioned spaces such as attic or crawl spaces. These duct systems in the unconditioned space have affected energy use and ventilation rates considerably (Modera, 1993). Andrews et al. (1998) showed that the duct system efficiency should be determined with the consideration of duct leakage. Leaky ducts in residential house can also contribute to mold growth and comfort problems in addition to high cooling and heating energy use (Moyer, Beal, Chasar, McIlvaine, Withers and Chandra, 2001). Parker and Vieira (2007) performed a study to quantify the annual cooling load components, and they found that 22% of the cooling energy loss comes from duct leaks and duct heat gain. They concluded that attic conditions and duct properties were important factors affecting the cooling/heating energy use in the residential building.

This paper presents results from a research involving the installation of a number of sensors at the case-study house and detailed analysis of the measured data including the heat loss/gain to the attic space by graphical and statistical methods. These measured data will be used to develop and verify the computer energy simulation model to run different scenarios of energy efficient feature of an attic and duct system specifically in the future research.

Measurement and Data Collection

The case-study building, a Habitat for Humanity house in Bryan, TX, is a low cost house constructed with volunteer labor and materials that utilize no or low-interest loans. The case-study house is a single-story house built in 1997, and total area is 1,100 ft^2. This house has a living room, a dining room, a kitchen, a utility area, 3 bedrooms, 1 ½ bathrooms, and a front and a back porch. Attic space (unconditioned space) is ventilated through gable louvers (1'-0" width x 1'-4" height) with wind blowing parallel to ridge. Table 1 shows the material specifications of the case-study house.

Table 1

Materials used in construction

Components	Materials
Floor	- 4" slab on grade and 30" deep ground beams which are 12" wide - Linoleum tile
Exterior walls	- Vinyl siding and ½" plywood wrapped with "Tyvek" moisture barrier - ½" gypsum, R-13 insulation - Composite 2x4" stud wall
Interior walls	- 2x4" stud wall - ½ "gypsum - Blown-in treated cellulose insulation.
Ceiling	- 5/8" fire coded gypsum board - 12" of blown-in fiberglass insulation.
Roof	- Composite shingles - 5/8" plywood deck - 2x4" trusses set at 24" on-center
Window	- Double pane clear with aluminum frame, without thermal break

The heating, ventilation and air-conditioning system consists of a 10.5 SEER (Seasonal Energy Efficiency Ratio) air-conditioning unit (2.5 tons), a furnace with 80% AFUE (Annual Fuel Utilization Efficiency), and a 0.56 EF (Energy Factor) domestic hot water system with 40-gallon tank size.

Installation of Sensors

Several sensors were installed to measure indoor / outdoor environmental conditions and energy consumption. Figure 1 shows the locations of each sensor in the house. A gas meter was installed at the rear side of the house, and was connected with the house's gas system and the data logger. In order to collect data from the case-study house, a data logger was located in the backyard of the case-study house. This data logger has 16 power inputs, 16 digital inputs, and 16 analog inputs, and can simultaneously monitor the analog, power and digital signals from the sensors located in the house. This data logger can be remotely operated, and data from logger can be downloaded using a computer program that is supplied by the manufacturer.

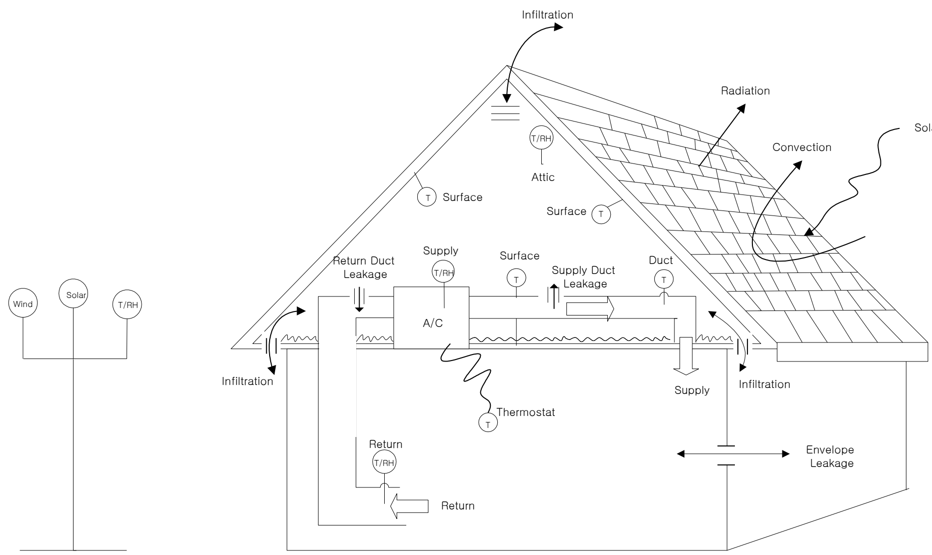

Figure 1: Diagram of sensor location.

Sensors were connected to the data logger to measure indoor / outdoor environmental conditions and the energy use of the house every 15 minutes. The temperature and humidity sensors were installed in the supply air duct, the end of the duct, attic space, attic surface, and the return grill (Figure 2). A flow meter was installed on the domestic hot water heater in the utility room, and was connected to the Btu meter at the rear side of the house.

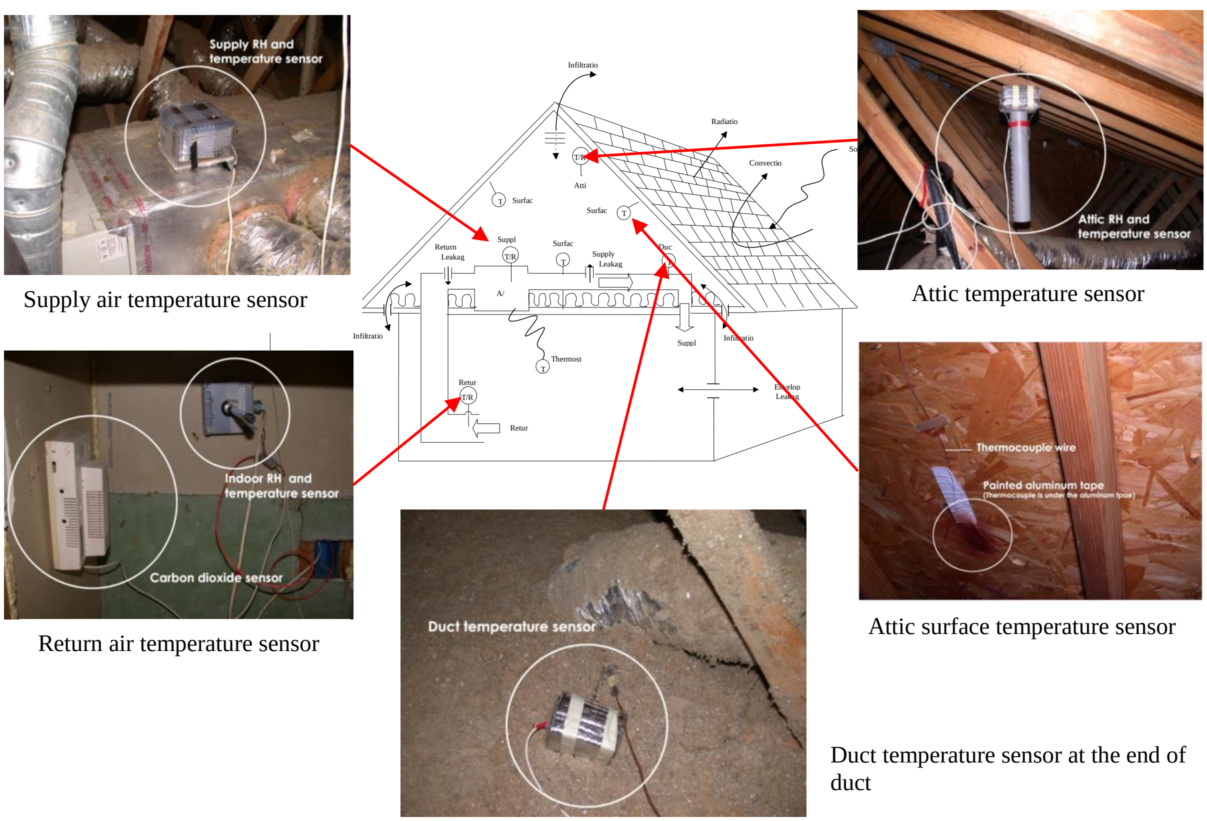

Figure 2: Installed temperature and relative humidity sensors in the attic space.

Collection of Data

The data collection process included: 1) polling, 2) error-checking, and 3) uploading of the data to the database. Polling data from the data logger at the case-study house was performed remotely with a computer using a telephone line connected to the data logger. The previous week's data, which is stored in the memory of the logger, were downloaded into the database every week. The error-checking task includes the inspection of downloaded data from case-study house. This included 1) examination of the maximum and the minimum value of the data, 2) graphical inspection to validate the pattern of the data, and 3) checking for any occurrence of data points that were shown by -99 at the series records, which means no data or out of range.

Data Analysis

Relationships between measured cooling energy use and attic, supply, return, duct, outdoor, surface temperature of inside roof deck, and solar radiation were assessed graphically and by use of the SPSS ver. 21 (IBM Corp., New York) to arrive at Pearson correlation coefficients and stepwise multiple regression analyses. Energy use analysis was limited to cooling energy during summer period because natural gas use for heating included domestic hot water use and pilot lights in the stove / furnace, and it is impossible to exclude them from natural gas use to achieve heating use only. Descriptions of the variables selected for cooling energy analysis are summarized in Table 2.

Table 2

Characteristics of measured data

Variables		Mean	St. Dev.	Sample #
Cooling Energy (Cooling E)	kWh	1.6206	.84193	336
Solar Radiation (SR)	$Btu/hr \cdot ft^2$	22.15	28.67	336
Attic Temperature (AT)	ºF	90.62	17.505	336
Supply Temperature (ST)	ºF	61.66	5.638	336
Duct Temperature (DT)	ºF	62.43	5.441	336
Return Temperature (RT)	ºF	68.03	1.574	336
Attic Surface Temperature (AST)	ºF	98.50	27.584	336
Outdoor Temperature (OT)	ºF	82.13	7.448	336

Results

The case-study house consists of a conditioned space, an unconditioned space (attic), and a duct system located in the unconditioned space. In order to investigate the duct heat loss / gain to the unconditioned space and the pattern of energy use, the thermal conditions and energy consumption of the case-study house were measured.

Figure 3 shows the measured attic, indoor, and outdoor temperature as well as natural gas use and cooling energy use from January 1 to December 31. As shown in this plot, the attic temperature covers a wider range than that of the outdoor temperature, while the indoor temperature (conditioned space) is in a narrow range between 70 ºF and 80 ºF. It can be clearly seen that the cooling energy use increases during the summer period due to air conditioner load. Also, the natural gas use increases during the winter period due to the use of the gas furnace. Gas use during the summer period is considerable due to domestic water heating, cooking, and five pilot lights (1-furnace, 1-DHW, and 3-stove).

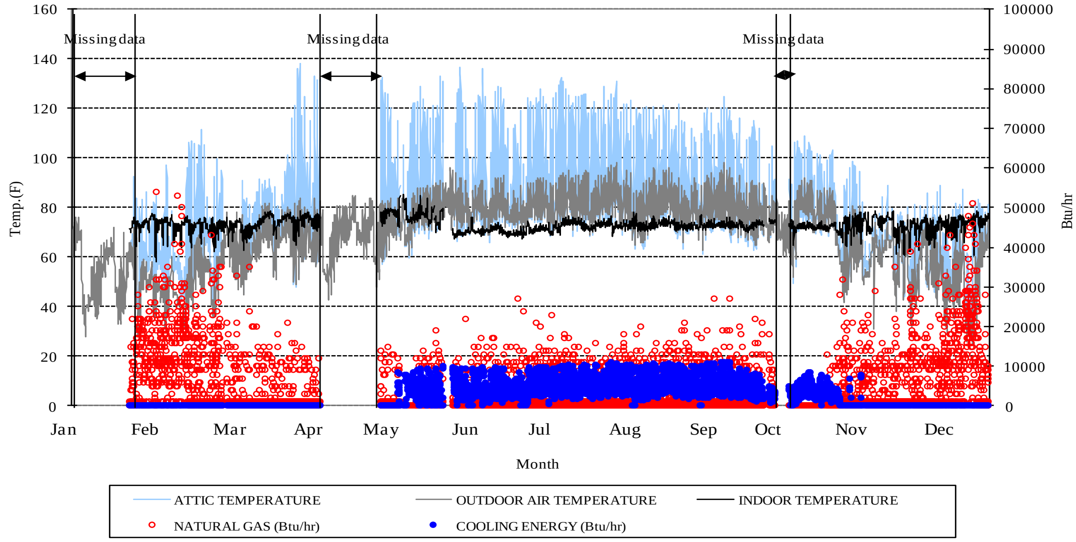

Figure 3: Measured attic, indoor and outdoor temperature, and heating and cooling energy

Figure 4 shows the temperature characteristics of the attic, supply, duct (close to diffuser) temperature, and the temperature difference (diffuser temperature – supply temperature) that was used to investigate the duct heat / gain in the attic space. According to the plot, the negative value of the temperature difference between the duct (close to diffuser) and the supply temperature indicates that there is the heat loss to the attic space because the attic temperature is lower than the supply temperature. On the other hand, the positive value of the temperature difference denotes that there is the heat gain from the attic space because the attic temperature is higher than the supply temperature.

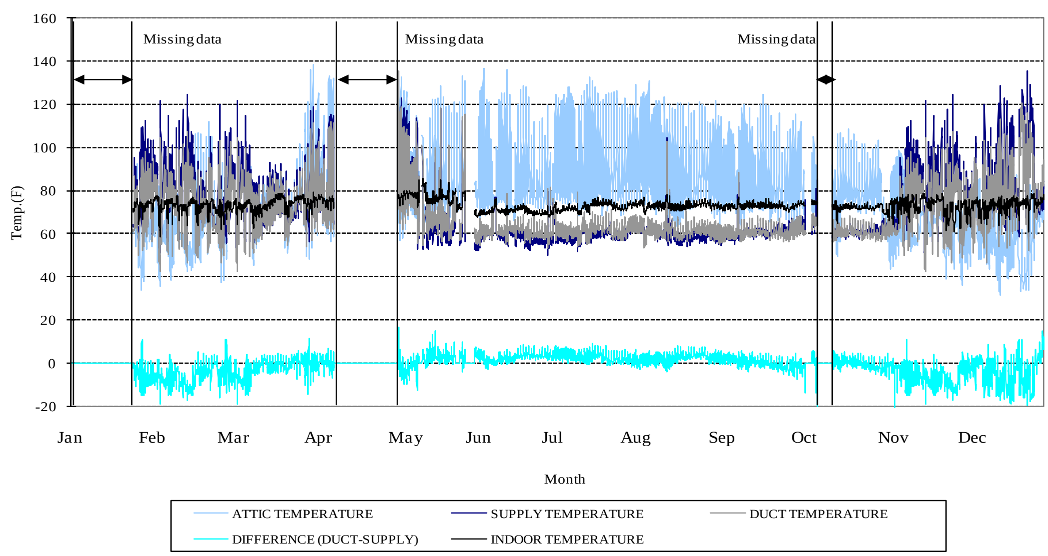

Figure 4: Measured attic, supply and duct temperature, and difference between duct and supply temperature

Measured Duct Heat Loss / Gain

In order to measure the energy loss from the duct in the attic space in detail, three measured temperatures from the return, supply, and end of duct (diffuser) were investigated. The area of supply duct and return duct are 170 ft^2 and 60 ft^2, respectively. The insulation level of the supply and return duct is R-6.

By inspecting the patterns of solar radiation, several clear days were selected to investigate the duct heat gain from the attic space. The maximum solar radiation measurement for several clear days was 309.2 Btu/hr·ft^2. The maximum hourly outdoor temperature for the same period was 99.2ºF, and the minimum measured outdoor temperature was 52.4ºF, representing a range of 46.8ºF and an average of 75.6ºF. The maximum attic temperature was 132.9ºF, and the minimum attic temperature was 62.9ºF. This represents a temperature range of 70ºF and average of 91.5ºF for several clear days.

During this period, the maximum attic temperature and outdoor temperature were recorded on July 14. It corresponds to the day when the air conditioner showed the maximum electricity use for cooling. Air conditioner electricity use showed that the maximum air conditioner electricity use was 3.1 kWh, occurring at 3:00 p.m. The average air conditioner electricity use during this period was 1.6 kWh.

Figure 5 illustrates the relationship between the attic temperature and Δt (the duct temperature – the supply temperature). The positive value of Δt (the duct temperature – the supply temperature) represents heat gain from the attic space to the duct system, while the negative value indicates heat loss to the attic space.

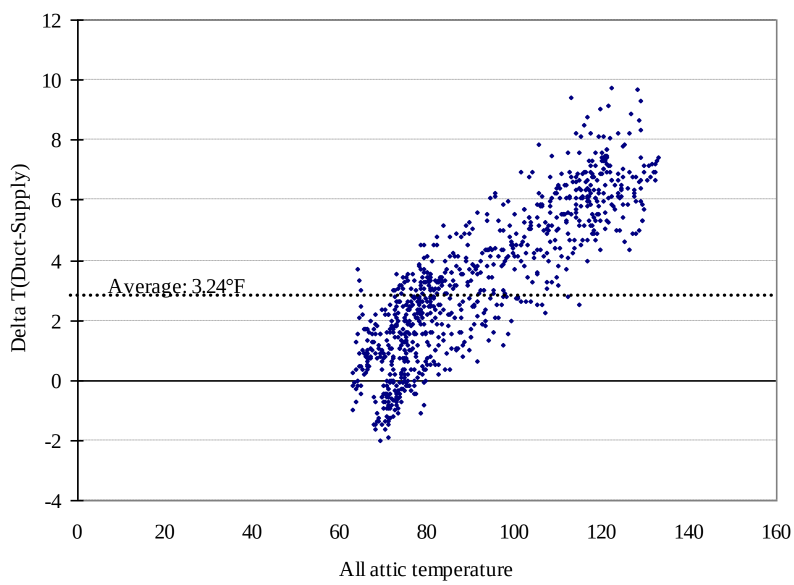

Figure 5. Plots of measured attic temp. vs. the difference between duct and supply temperature

The plot shows that the maximum Δt (the duct temperature – the supply temperature) was 9.8 ºF, and the average Δt was 3.2 ºF on selected days. The pattern of the plots also shows the strong linear relationship between attic temperature and Δt (duct temperature – supply temperature) as the attic temperature reaches high.

Statistical Analysis

Analyses of measured variables such as different temperatures, solar radiation, and their respective influences on cooling energy use were performed using Pearson correlation and multiple regression analysis.

Table 3
Pearson correlation coefficients for cooling energy use and other variables*

Predictive variable	Cooling E	SR	AT	ST	DT	RT	AST
SR	0.427						
AT	0.807	0.797					
ST	-0.552	0.186	-.088				
DT	-0.247	0.494	0.278	0.922			
RT	0.218	0.44	0.505	0.493	0.659		
AST	0.697	0.911	0.969	.019	0.38	0.503	
OT	0.805	0.604	0.892	-0.236	.076	0.34	0.826

* Cooing E, cooling energy; SR, solar radiation; AT, attic temperature; ST, supply temperature; DT, duct temperature; RT, return temperature; AST, attic surface temperature; OT, outdoor temperature.

According to the result (Table 3), attic temperature was shown to correlate most highly with cooling energy use (r = 0.807), followed by outdoor temperature (r = .805) and attic surface temperature (r = .697). This finding indicates that accurate attic temperature calculation in the computer simulation model is critical to derive a valid simulation model since the attic space is a direct environmental condition of duct system.
Stepwise multiple-regression analysis including all variables yielded a predictive equation for cooling energy use in which attic temperature alone yielded an adjusted R^2 value of 0.65.
Cooling energy = -1.896 + 0.039 × AT (Adj. R^2 = 0.65) (1)

The stepwise addition of duct temperature, solar radiation, return temperature, and outdoor temperature increased the adjusted R^2 value to 0.918; the remaining variables (supply temperature and attic surface temperature) did not contribute further to the predictive value of the equation.
Cooling energy = 2.421+0.046×AT–0.079×DT (Adj. R^2 = 0.892) (2)
Cooling energy = 0.985+0.055×AT–0.067×DT–0.003×SR (Adj. R^2 = 0.912) (3)
Cooling energy = -1.938+0.052×AT–0.078×DT–0.002×SR+0.057×RT (Adj. R^2 = 0.917) (4)
Cooling energy = -1.155+0.057×AT–0.079×DT–0.002×SR+0.053×RT-0.011×OT (Adj. R^2 = 0.918) (5)

The multicollinearity between the independent variables was tested by finding the VIF (Variance Inflation Factor). Cohen et al. (2003) suggested VIFs of 10 or more to be the rule of thumb for concluding VIF to be too large. Therefore, the authors selected the threshold value of VIF to drop redundant independent variables as 10. After examination of the VIF of variables of all equations, equation 5 showed high value on VIF (12.2). Not surprisingly, outdoor temperature was highly correlated with attic temperature and solar radiation (r = 0.892 and 0.604, respectively). Therefore, equation 5 is not a valid predictive equation because of multicollinearity issue and the least influence on adj. R^2 improvement (0.917 to 0.918).

The attic and duct temperature were found to have significant effects on the cooling energy use because the adjusted R^2 is increased to 0.892 from 0.65, while the solar radiation and return temperature have little effects on the cooling energy use (adjusted R^2 is increased from 0.892 to 0.917 as exiguous).

Discussion

The measured data is from one single house, so it may not be appropriate to generalize the results to all other single family residences. However, most houses (such as Habitat for Humanity) were built similar way with the similar floor plan, material, and HVAC systems, and weather pattern in its location is the important factor to account for the energy use. Therefore, this measurement can be a reference to understanding the factors that have impacts on the energy use of residences.

From the plots with the measured data, it was found that average temperature increment from blower (supply temperature) to the end of duct (duct temperature) was 3.2 ºF, and maximum temperature increment was 9.8 ºF. It indicates that if the supply air temperature right after the blower at the air conditioner is about 55 ºF, the temperature at the diffuser in the room can be up to around 65 ºF in hot summer. This results in continuous AC running, and consumes more cooling energy. In addition, application of energy-efficient technologies in designing attics for residential buildings is deemed necessary to reduce the attic temperature and prevent heat gain from attic space to the duct system.

From the statistic analysis, it was found that attic temperature is the most significant factor on cooling energy use, and the air temperature at the diffuser is the next significant factor. Therefore, if the duct systems are located in unconditioned spaces (i.e., the attic space or crawl space), measures such as relocating the duct systems to conditioned spaces, adding the radiant reflective insulating barriers on the face of inside the roof, adding more ventilation in the unconditioned space, or increment of insulation level of the duct system need to be considered for possible energy savings when designing residential houses.

Future Work

These data will be used to develop and calibrate the simulation model in the future research. In order to develop a calibrated simulation model of the case-study house, a series of simulations will be used to assess the improved accuracy by comparing them to the measured data. The calibration process includes the comparison of the simulated versus measured hourly attic temperature, zone temperature, electricity use, and natural gas use using a specially prepared weather file that includes measured weather data corresponding to the same period as the other measurements. After verifying the simulation model, the simulation model will be used to run different scenarios of energy efficient feature of the attic and duct system specifically.

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