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Modeling and Simulation of Residential HVAC Systems Energy Consumption

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Abstract

Saudi Arabia is characterized with high temperature, humidity, and dust storms. The air conditioning systems are an essential component in daily life. 60% of the energy consumed in the residential area is used by air conditioning systems. The aim of this paper is to build a residential thermal HVAC model, which could predict the amount of energy consumption required to get the comfort level using Matlab/Simulink. In this model the different physical properties of the building, weather, and heating gains are taken to account. The results of energy consumption obtained from Matlab/Simulink model are based on using the actual hourly outdoor temperature for a selected day of 2012 compared to the average outdoor temperature of the same selected day. The results of energy consumption for the actual and average temperatures are almost identical. For this reason, the results of total energy consumption are presented in this paper for every day of the annual year of 2012 based on the average hot and warm outdoor temperatures (7 1/2 months), and cool and cold temperatures (4 1/2 moths).

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Keywords: Air conditioning; residential thermal model; energy consumption;

1. Introduction

Primary energy consumption in the residential areas in Saudi Arabia is the HVAC system which accounts for about 60% of the energy used in the houses. Space-conditioning has become on the rise through the Kingdom of Saudi Arabia due to the severe hot temperature and high humidity. To evaluate the energy consumptions used by the space-conditioning, thermal modelling and simulation of the house must be developed. A simple space thermal heating model to evaluate the electric and heating energy consumption of residential HVAC systems has been studied[1].

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They implemented the model using Matlab for different scenarios to show the impact of different technology adoption to be assessed. Also, they validated their results in comparison with actual metered residential load data. A focus on specific equipment and their regulation in developing the thermal and energy performance of buildings and HVAC system has been presented in[2]. They developed a numerical model application for office building in order to test its robustness and the results were compared with changing of locations. A simplified building HVAC model which predicts the temperature variation within the building and estimates the amount of energy required to get the comfort level using Matlab/Simulink has been proposed in[3]. They verified the results accuracy of their model with IEA Building Energy Simulation Test. The main advantage of this model is its simplicity and been less computational. GridLAB-D has been used for aggregated modeling and control of air conditioning loads for demand response[4]. They proposed aggregated model is based on a general second-order equivalent thermal parameter, which considers both the air and mass temperature dynamics of individual HVAC for ON/OFF cycle systems.
HVAC central cooling/heating system provides a space heating which is controlled based on temperature and time to coincide with the occupancy pattern. The cooling/heating demand based on a combination of comfort aspiration, economic status, and living habit. There are several factors affecting the space cooling/heating: weather conditions, physical characteristics of the house, characteristic of heating system, occupant requirements, and internal heat gains. The impact of thermal insulation on the thermal energy demand of a passive house in the gulf regions has been reported in[5]. The study compares the annual cooling demand from simplified Global Sustainability Assessment System. They found out the discrepancies in predicted annual cooling demand between the simplified and detailed models did not exceed 15% for both static and dynamic operations of the passive house. Energy optimal control of a residential space-conditioning system based on sensible heat transfer modeling has been presented in[6]. The thermal comfort and energy efficiency are compared under the different schemes. It has been found that proportional control is advantageous to the two-position control for the thermal comfort while there is not much difference in energy consumption between the control schemes. A real time dynamic house thermal model identification for predicting HVAC energy consumption has been conducted in[7]. The autoregressive model with exogenous inputs is used to identify the house thermal model. They show experimental results with 15% energy prediction error in both heating and cooling modes of the HVAC system. Physically based electrical load models for HVAC system has been implemented and tested in[8]. These models are based on energy balances between the internal air, the dwelling constructive elements, the conditioner appliances, and the external environment through a discrete state-space equations. Their simulated results have been compared with data collected for short periods during one year in different cities and for different load performances.

The paper is organized as follows. Section II, weather environmental measurement for outdoor temperature, humidity, irradiation, and wind speed in Dhahran area for year 2012. Section III presents the mathematical model for the second order thermal model of a house using Matlab/Simulink environment. The simulation results and discussion are explained in section IV. Section V is presented the conclusion. Most previous studies evaluated the energy consumption over a few selected days throughout the year. A difference in this paper is the evaluation of the energy consumption for every day of one complete year of 2012 for using real environmental data measurement. The purpose of an extended study is to be able to predict and evaluate the energy consumption and estimate the peak load at certain times of the day and the year.

2. Weather and environmental measurement

The weather environmental measurement was obtained through the Research Institute at KFUPM, Dhahran Area, from January 1 to December 31, 2012. The data was collected based on average hourly irradiation, relative humidity, wind speed, and outdoor temperature. Figure 1 shows the level of irradiation for Dhahran area reaching between 600 to above 1000 W/m2 winter to summer season, respectively.

Relative humidity is changing between 15%-93% through the year as shown in Fig. 2. It is low during May and June compared to other months of the year.

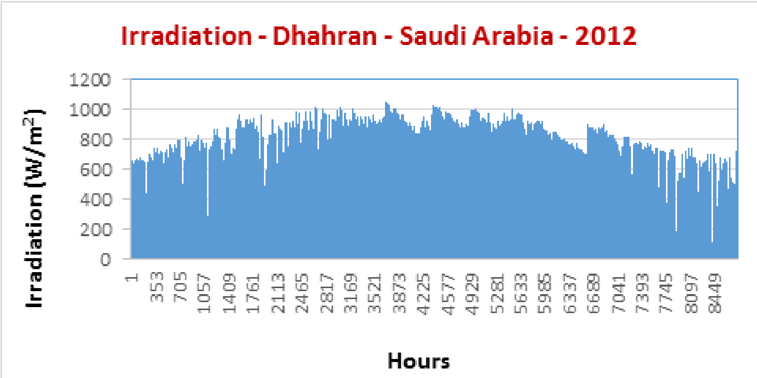

Fig. 1. Irradiation of Dhahran area in Saudi Arabia 2012.

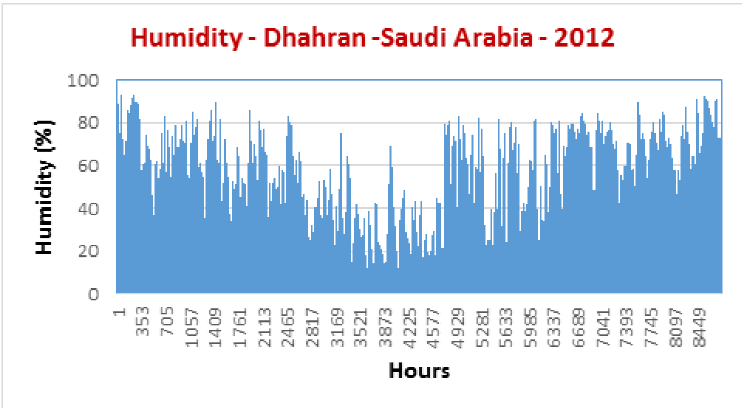

Fig. 2. Humidity of Dhahran area in Saudi Arabia - 2012.

Fig. 3 shows the wind speed of Dhahran area. It can fluctuate between 3 m/s to 13 m/s through the year. Air outdoor temperature for Dhahran area is depicted in Fig. 4. The air outdoor temperature is changing between 13°C during winter to over 45°C during summer. It is noticed that the air outdoor temperature is above 30°C for most of the year.

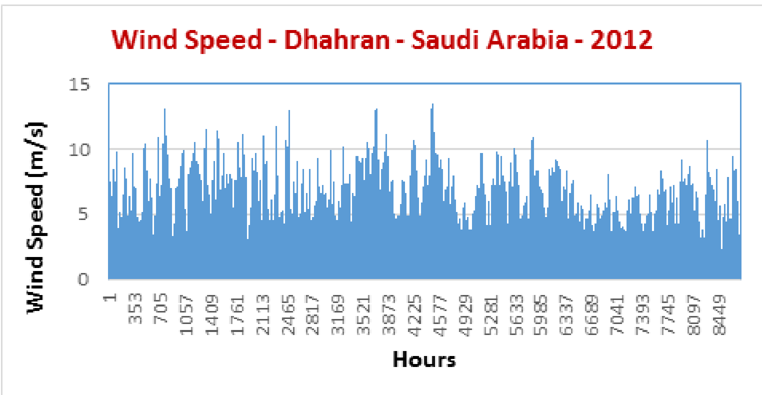

Fig. 3. Wind speed of Dhahran area in Saudi Arabia - 2012.

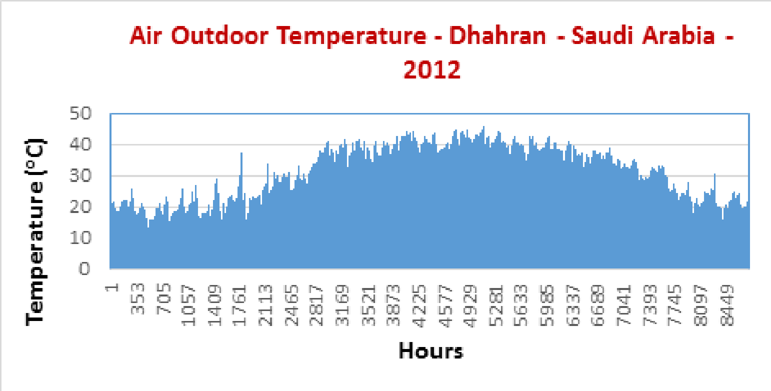

Fig. 4. Outdoor temperature of Dhahran area in Saudi Arabia 2012.

3. Second-order Thermal Model of a house development using MATLAB

The thermal circuit of the second order heat balance is shown in Fig. 5. The heat balance for the air temperature node (T_a) is presented in Eq. (1) as:

$$\dot{T}_a(t) = \frac{1}{C_a}\left[U_m \cdot T_{mass}(t) - (U_a + U_m) \cdot T_a(t) + Q_a + U_a \cdot T_o(t)\right] \quad (1)$$

The heat balance for the mass temperature node (T_{mass}) is presented in Eq. (2) as:

$$\dot{T}_{mass}(t) = \frac{1}{C_m}\left[U_m \cdot \left(T_a(t) - T_{mass}(t)\right) + Q_m\right] \quad (2)$$

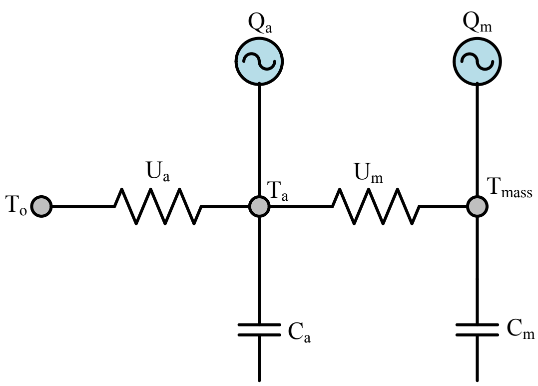

Fig. 5. Thermal circuit model of home heating/cooling system.

Where:

T_a	:	the indoor air temperature
T_{mass}	:	the inner mass temperature (due to the building materials and furnishing)
T_o	:	the outdoor temperature
C_a	:	the thermal mass of the air
C_m	:	the thermal mass of the building materials and furnishings

U_a : the conductance of the building envelope
U_m : the conductance between the inner air and inner solid mass
Q_a the heat flux consists of three main factors: Q_i (internal heat gain), Q_s (solar heat gain), and Q_h (the heat gain from cooling/heating system)
$Q_a^{off} = Q_i + Q_s \qquad Q_a^{ON} = Q_i + Q_s + Q_h$
Q_m : the heat flux to the interior solid mass

The SIMULINK block diagram of the second order thermal model of a house is presented in Fig. 6. There are six input variables the temperature set point T_s, the cooling air of the HVAC T_{HVAC}, the air outdoor temperature T_o, the internal heat gain Q_i, the mass heat Q_m, and the solar heat Q_s. There are two outputs: the air indoor temperature T_a and the mass temperature T_m. The floor plan of the guesthouse used in the conducting study is shown in Fig. 7. It consists of one bedroom, one leaving room, kitchen, and bathroom. The dimensions are in centimeter as shown in the Fig. 7.

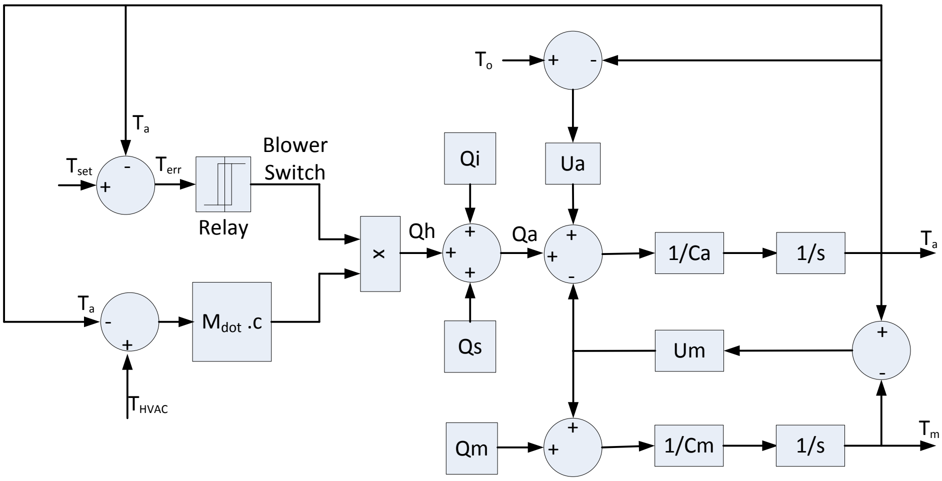

Fig. 6. Second-Order Thermal Model of a House.

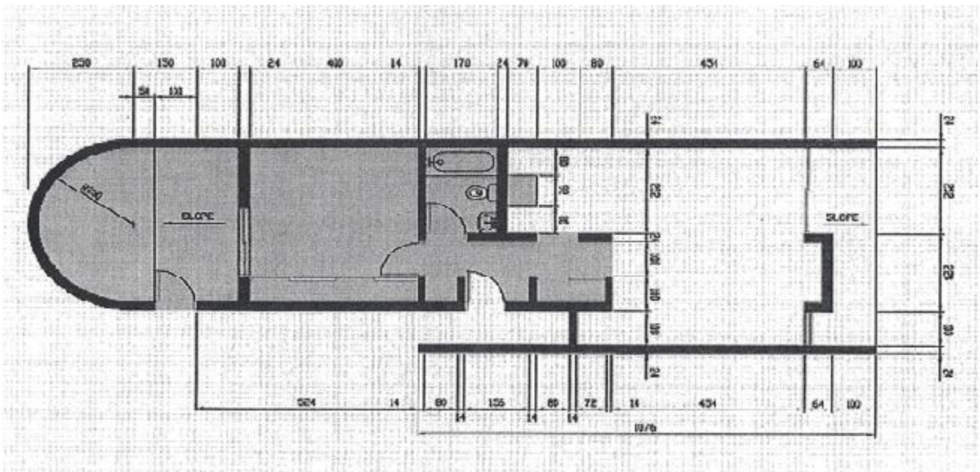

Fig. 7. Floor plan of the guesthouse at KFUPM, Dhahran, Saudi Arabia.

The MATLAB program is generated based on the thermal circuit model for a house considering the following parameters as presented in Table 1.

Table 1. Thermal house model data

item	Amount	Unit	Item	Amount	Unit
Length of house	8.5	M	Rw	11	F.ft^2.hr/Btu
Width of house	5.7	M	Rf	19	F.ft^2.hr/Btu
Height of house	3.5	M	Rc	30	F.ft^2.hr/Btu
Height of window1	2	M	Rd	3	F.ft^2.hr/Btu
Width of window1	2.2	M	Rg	2	F.ft^2.hr/Btu
Height of window2	2.2	M	Qi	1000-8500	Btu
Width of window2	3.5	M	Qs	0-2000	Btu
Window area	12.1	M^2	Qh	36 - 48	KBtu
Wall area	229.3	M^2	Qm	1000-3500	Btu
Roof area	48.45	M^2	Tset	75	F
Door area	2.64	M^2	Mhvac	2400-3600	Kg/s

The internal heat gain, Q_i, is varying through the day. It will not be constant during 24 hours. In addition, the solar heat gain, Q_s, is varying through the day based on the sun penetrating through the windows. The mass heat gain may change between day and night. Indoor air temperature and mass temperature can be evaluated using all factors of heat gains in the model to get accurate behaviour of the HVAC system. Table 2 shows all influential parameters on the HVAC system operation.

Table 2 Heat gain parameters for warm and hot weather

Time	Q_s (Btu)	Q_i (Btu)	Q_m (Btu)
12 AM – 6 AM	0	1500	1000
6 AM – 12 PM	2000	3500	2500
12 PM – 6 PM	2000	8500	3500
6 PM – 9 PM	0	8500	3500
9 PM – 12 AM	0	3500	1500

4. Simulation results

HVAC airflow rate used in this simulation is equivalent to a 4-tons air conditioner system. The outdoor temperature used in this simulation from July 4, 2012 is taken in the Dhahran area based on average hourly temperature. Fig. 8 shows two subplots. The top subplot represents the outdoor air temperature (T_0), indoor air temperature (T_a), set point temperature (T_s), and mass temperature (T_m). The bottom subplot shows the duty cycle in percentage, period or cycle length in minutes, and the air condition ON time in minutes. We can notice that the duty cycle of the air condition changing through the day and night with association with outdoor temperature. From midnight until 6 Am the duty cycle is more than 20% and less than 25% and the period length more than 10 minutes, meaning the air condition is turned on for less than 3 minutes and off for more than 9 minutes. At 6 Am, when we have the sunrise and household starting their activities, the duty cycle starts going up almost 34%, and at the same time the HVAC time on reaches nearly 10 minutes per cycle. At midday, the HVAC time on goes up. From 12 PM to 6 PM, the outdoor temperature exceeds 105 ^{o}F, and the duty cycles goes up almost 59% and the period or cycle length reaches around 8 minutes, which means the A/C is on for 5 minutes and off for 3 minutes. At 6 Pm, the sunset and the outdoor temperature starts declining. The duty cycles go down almost 50% with period or cycle length around 8 minutes until 9 PM. Between 9 PM and midnight, the outdoor temperature continues in declining and the household activities are reduced close to bed time and the duty cycle goes to 30% with A/C turning for short period of time less than 3 minutes. The number of cycles is 159 per 24 h. The total time operation for the A/C system is 9.4554 h.

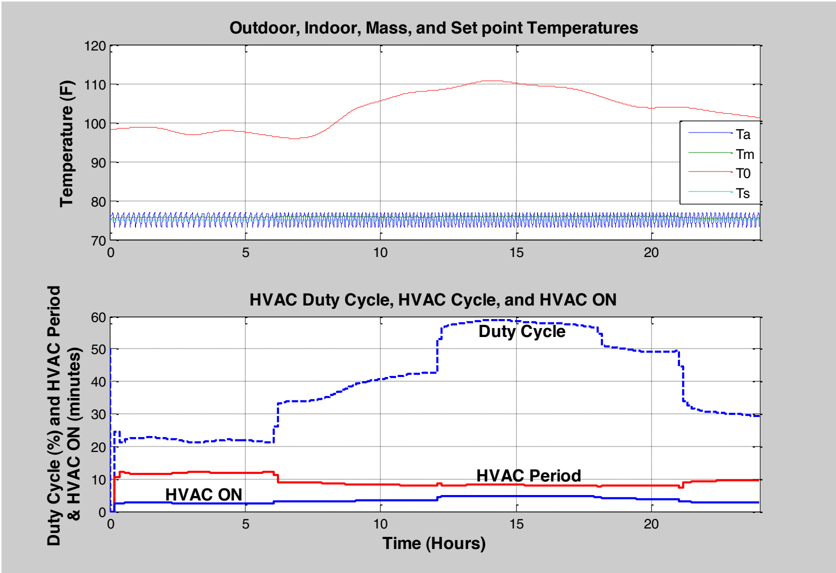

Figure 8: Top plot: Outdoor, Indoor, Mass, and Set point Temperatures, Bottom plot: Duty Cycle, Period Length, and HVAC time on

We consider the average outdoor temperature through the 24 hours period for July 4, 2012. Fig. 9 shows the average outdoor temperature is 103.223 ^{o}F (39.569 ^{o}C). All other parameters of the house model are unchanged. The simulation results show not much difference in reference to the outdoor temperature changing through the day. The number of cycles is increased from 131 to 165 per 24 h. The total operation time for the A/C system is 9.4731h, which is not different from using actual outdoor temperature or average outdoor temperature per day. These results will help us to evaluate the energy used by the HVAC during week, month, and year.

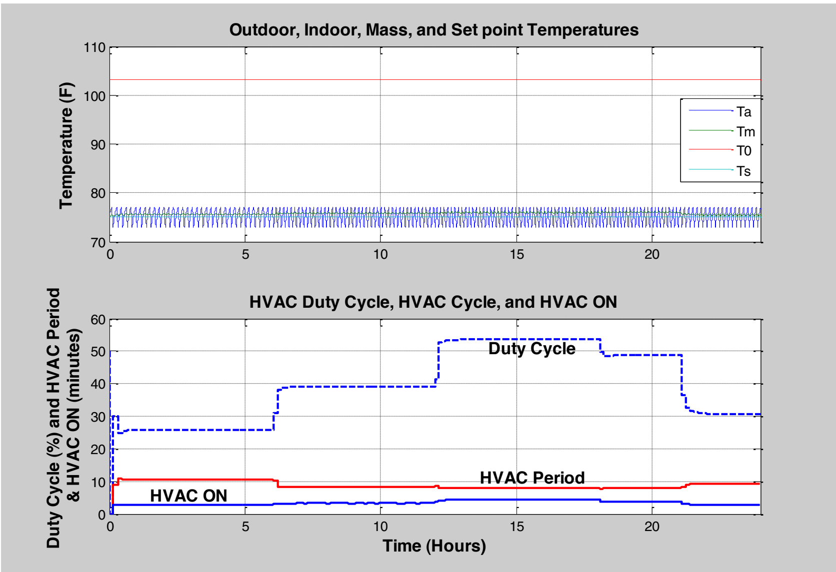

Figure 9: Top plot: Outdoor, Indoor, Mass, and Set point Temperatures, Bottom plot: Duty Cycle, Period Length, and HVAC time on

Now we consider the average outdoor temperature through the warm and hot days of the 7 1/2 months period of year 2012, which is T_{0AVG} = 91.122 ºF (32.85 ºC). Fig. 10 shows the average outdoor temperature, indoor, mass, and set point temperatures, duty cycle, period length, and HVAC time on. All other parameters of the house model are unchanged.

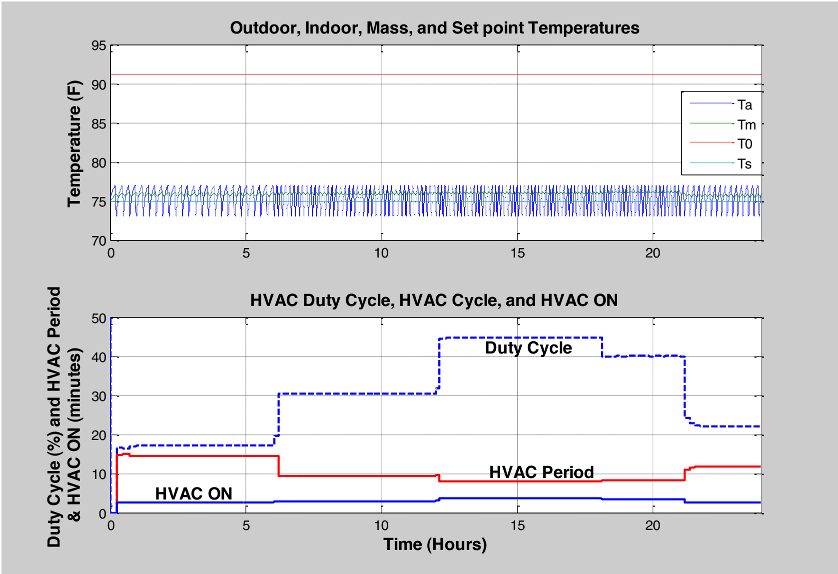

Figure 10: Top plot: Outdoor, Indoor, Mass, and Set point Temperatures, Bottom plot: Duty Cycle, Period Length, and HVAC time on

From midnight until 6 AM the duty cycle is 17.1% and the period length more than 15 minutes, meaning the air condition is turned on for less than 3 minutes and off for more than 12 minutes. At 6 AM, the sunrise and household starting their activities, the duty cycle goes up almost 30%, period length goes slightly below 10 minutes, but the HVAC time on goes up until mid-day. After mid-day, the duty cycles goes up almost 45% and the period or cycle length reaches around 8 minutes, which means the A/C is on for 3.6 minutes and off for 4.4 minutes. At 6 PM, the sun sets and the outdoor temperature starts declining. The duty cycles goes down as much as 40% with period or cycle length around 8 minutes until 9 PM. Between 9 PM and midnight, the duty cycle goes as much as 22% with A/C turning for short period less than 3 minutes. The number of cycles is 145 per 24 h. The total average time operation of the A/C system for one day is 7.3834 h.

In the winter season, we consider the average outdoor temperature through the cool and cold days of the 4 1/2 months period (January, February, 1/2 March, November, and December), which is T0AVG = 64.40 ºF (18 ºC). Design heating load depends on indoor-outdoor temperature difference. Fig. 11 shows the average outdoor temperature, indoor, mass, and set point temperatures, duty cycle, period length, and HVAC time on. The duty cycle is almost 7%, period length is 34 minutes and the HVAC is on for 2.35 minutes and off for 31.65 minutes. The number of cycles is 44 per 24 h. The total average time operation of the A/C system for one day is 1.758 h.

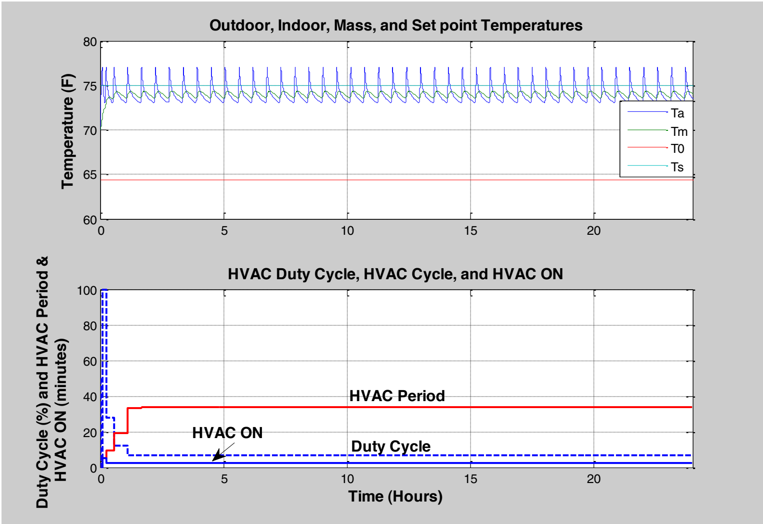

Figure 11: Top plot: Outdoor, Indoor, Mass, and Set point Temperatures, Bottom plot: Duty Cycle, Period Length, and HVAC time on

In central air conditioning units, there are three motors are connected to the system. Motor compressor, motor condenser, and motor blower. The motor compressor and motor condenser turn on and off together. The blower motor fan works continuously. Dhahran city in Saudi Arabia has 7 1/2 months of warm, hot, and humid weather and 4 1/2 mild and cold. Based on climate data obtained from the Environment Center at the Research Institute at KFUPM for 2012, the average temperature for the warm and hot season is 91.122 ^{o}F (32.85 ^{o}C) and the average temperature for mild and cold weather is 64.4 ^{o}F (18 ^{o}C). We selected one hot day, 4th of July 2012 as actual temperature through the day and as average daily temperature to evaluate the energy consumption used by a 4-tons air conditioning system ON/OFF cycle presented in Table 3. We assumed the efficiency of three motors are the same and equal to 87% for the consistency of the evaluation of the energy consumptions. Also, we evaluated the energy consumed for the year 2012 based on the average temperatures for cooling and heating seasons. Table 3 shows the HVAC ON time, number of cycles and energy consumption for 4 July 2012. We obtained the data based on actual temperature through the day and based on the average day temperature as shown in Table 3. There is no difference in energy consumption for the actual or average temperature for the selected one hot day during the summer. The only difference is in the number of cycles per day, which is the number of cycles for the average temperature higher than the actual temperature. This is true because the HVAC system will stay on for longer duration when the temperature is higher before turning off again.

Table 3 HVAC ON time, number of cycles/day, and energy consumption/day for 4 July 2012

Outdoor Temperature	T_ON Time (H)	# of Cycles / day	Energy used (kWh) / day
Actual	9.4554	159	58.5755
Average (103.2243 ^{o}F)	9.4731	165	58.6659

We are using 4-tons HVAC system data presented in Table 4. Table 4 shows the HVAC ON time, number of cycles and energy consumption based on the average warm and hot season temperature. The HVAC is turned on for about 7.4h/day. The number of cycles is 145 per day. The energy consumption is 48 kWh/day. The total energy consumed for 230 days (7 1/2 months warm and hot season) is 11040 kWh. The total energy consumed for 135 days (4 1/2 months mild and cold season) is 896 kWh. The total energy is consumed per year is 11936 kWh.

Table 4 HVAC ON time, number of cycles/day, and energy consumption/day for average warm and hot temperature of 2012 using 4-tons HVAC system

Outdoor Temperature	T_ON Time (H)	# of Cycles / day	Energy used (kWh) / day
Hot – Average =91.1 ^{o}F	7.38	145	48
Cold – Avg = 64.4 ^{o}F	1.76	44	6.64

5. Conclusions

Modeling and simulation of residential HVAC system energy consumption has been investigated using Matlab and Simulink environment for every day of one year. Weather data measurements for the Dhahran area have been presented for the year 2012. A second order model has been used to model the element building envelope and heating system. First, the energy consumption was evaluated based on hourly outside temperature measurement for one selected day. Secondly, the energy consumption was evaluated based on average outside temperature through the same day. In both calculations, the energy consumed by the HVAC system was found to be identical. Based on the finding, the energy consumption by the HVAC system was calculated using average yearly temperature. The yearly measured outside temperatures were divided to two sectors: 7 1/2 months for the hot season and 4 1/3 months for the cool and cold season. The total energy evaluated for 2012 was 11936 kWh. This outcome could be generalized to evaluate energy consumptions and peak load for a compound neighbourhood in Saudi Arabia.

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