Thermal modelling of the building and its HVAC system using Matlab/Simulink

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***Abstract*- The aim of this paper is to develop a simplified building-HVAC system which could predict the temperature variation within the building and estimate the amount of energy required to get the comfort level using the Matlab/Simulink. For the estimation, this model would take into account of different physical properties of building, location of building, weather, gains and heating system. As a case study, the model has been implemented to a semi-detached dwelling with all the real data. The results obtained from Matlab/Simulink are then compared with another software which is verified against IEA Building Energy Simulation Test (IEA BESTEST) building load and HVAC tests. The main advantage of this model is its simplicity and less computational resources.**

Keywords – Building modelling, Thermal modelling, HVAC system modelling

I. Introduction

The UK government is committed to play a major role in fighting with climate change. It has set legally binding emission targets to cut the carbon emission by 80% from the levels in 1990 by 2050, with an interim target of 34% by 2020. On 15th July 2009, the government published UK Low Carbon Transition Plan White Paper which sets strategy for reducing the energy demand for heating, transport and electricity which includes energy efficient buildings and transforming the way of heating homes.

New and existing homes need to be made significantly more efficient to meet the above targets. Approximately 50 percent of the UK's carbon dioxide emissions can be related to the buildings, of which over 27 percent originate from residential housing. When developing strategies to minimise energy consumption within buildings it is important to understand the dynamics of energy generation and losses. Thermal model of building can provide techniques for a range of building design and analyse problem including building energy demands, passive design, environmental comfort and the response of heating system.

Different approaches to model the heat flow in the building can be found in literature with different methods such as Lumped node method, finite element or finite difference method and impulse response factor method. Impulse response factor method has the accuracy problem and is not suitable for dynamic plant simulations where simulation time step is necessarily low [1]. Finite element or finite difference methods is accurate but are very complex and require more computational resources. Lumped node method is the simplest and requires less computational time. In Lumped node method, the construction elements are broken down into a numbers of temperature-uniform elements about which an energy balance can be expressed.

First attempt on low-order thermal response was done by Lorenz and Masy [2], which in turn formed the basis of analytical parameter estimation for the 5-parameter 2nd – order model of Crabb et al. [3]. Further to that, Gouda et al. [1] proposed an optimization method using the constrains for the element modelling of room space based on lumped capacitances. Using this optimised method Gouda et al. [4] modelled room for analysing the control system response of HVAC system. However, not much detail about solar gain through windows was given. Sukla and Jenkins [5] has used lumped node method to model the house taking into account of heat loss and thermal capacity however the influence of other factors such as solar radiation, ventilation and gains are not included in the model. Bertagnolio & Lebrun [6] have used 1st order model for modelling for building elements which is implemented in Engineering Equation Solver. In this paper, 2nd – order method is used for modelling the building elements.

The interaction between a heating system and thermal demand in a building is complex due to different factors such as weather, occupant's behaviour, economic status of occupants, physical properties of building and characteristic of heating system. This complex system requires a building performance model and simulation tool that is capable of evaluating the thermal demand of a building.

Thermal demand of a building may be considered as: space heating, hot water demand and cooking [7]. Space heating mainly depends on the time of year, time of day, house design, occupancy pattern and performance of heating system. The pattern of hot water use in the building is irregular and quantity varies widely. However, in case of dwelling hot water is mostly used in the morning and in the evening. For cooking, gas or electricity may be used as fuel and the heat produced during cooking also contributes to the thermal gain of the property, though not significantly. In this paper, space heating energy demand which contribute the most is only considered.

Space heating is provided by central heating system which is controlled based on temperature and time, which is made to coincide with the occupancy pattern. The heating demand is a combination of comfort aspiration, economic status and living habit. Different factors that influence the space heating can be divided into five categories:

- Physical characteristic of the house: U-values, thermal capacity, internal heat transfer, infiltration rate etc.
- External weather condition: temperature, solar radiation, wind speed etc.
- Characteristic of heating system: system efficiency, time constant, control etc
- User requirements: temperature level, window opening etc

- Internal heat gain: due to electrical appliance and occupant's behaviour.

Using this model the carbon emission due to the heating of the house can also be determined with different level of housing insulation and comfort level within the building which can be set to fix temperature all year or vary through the year as people adapt to change in outside temperature (adaptive comfort temperature).

II. Model Description

A. Building model

Lumped node method is used for the modelling of the building. In lumped node method the construction elements is break-up into different number of element having uniform temperature about which an energy balance can be expressed. The optimised second order lumped parameter method proposed by Gouda et al. [1] , is used as building thermal model. This model can represent a wall, floor or roof of 'n' layers.

A construction element consists of several layers of different materials and thickness, each layer having its own properties such as thermal conductivity, specific heat capacity and density. In this model, a construction element, irrespective to number of layers, is represented by three lumped thermal resistance (R_1, R_2, R_3) and two thermal capacitance (C_1, C_2) as shown in figure 1.

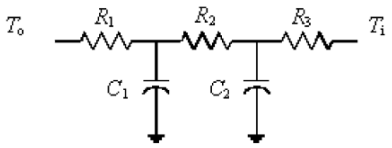

Figure 1: 2nd order lumped parameter construction element

Where R_1, R_2 and R_3 are fractions of total resistance R_T and C_1 and C_2 are fractions of total capacitance C_T for the construction element. T_o and T_i represents the outer and inner wall temperature of the room. When representing an inner wall, T_o represents the wall temperature of adjacent room.

Along with building element modelling, building space is modelled by two first order equation representing room air moisture and room air temperature. Ventilation and infiltration rated is calculated using a equation developed by National Bureau of Standards (USA).

B. Solar radiation model

Solar gains are the main contributor for the heat gain in a house. It reduces the requirements of space heating system; however the gains vary with change in the sunlight. The magnitude of solar gains depends on orientation, latitude, cloud cover and shading by tree and other buildings. Solar gains are mainly through the windows. Solar radiation also affects the external surface of the dwelling, such as walls and roofs by warming them and thus reducing the rate of heat loss. However, the effect of these is relatively low compared to the gains through the windows. Solar gains through windows depend on the glazing area and the transmission properties of the glass.

To estimate the solar radiation incident on any surface at any orientation, diffuse and direct fraction of incident solar radiation should be known. Solar radiation model presented by Underwood & Yik [8] gives an estimation of total solar radiation on a tilted surface. This model is the combination of two sub models in which, the first sub model estimates the diffuse and direct fraction from the global horizontal solar radiation whereas the second sub model uses these values to determine the solar radiation incident on the building surface. The assumption made is that the sky and ground-reflected radiation to be isotropic and surface is not shaded.

C. Heating system model

The current practice to heat building is through hot water emitter controlled by valve. Hot water supplied from central boiler is delivered at constant temperature and the valve controls the water flow rate, which is applied to the radiator to produce the heating.

For hot water emitter, a general third order model is used to represent a heat exchanger and its water connection.

$$C_W \frac{dT_{W1}}{dt} = 3m_w c_p (T_{Wi} - T_{W1}) - K(T_{W1} - T_i)^n \tag{1}$$

$$C_W \frac{dT_{W2}}{dt} = 3m_w c_p (T_{W1} - T_{W2}) - K(T_{W2} - T_i)^n \tag{2}$$

$$C_W \frac{dT_{Wr}}{dt} = 3m_w c_p (T_{W2} - T_{Wr}) - K(T_{Wr} - T_i)^n \tag{3}$$

Where, C_w is the overall thermal capacity (includes the radiator material and water), K is the overall heat transfer coefficient of the emitter and n is the heat transfer index.

A control valve for liquids can be expressed on the basis of the relation between the flow rate passed by the valve and the position of the valve at a constant pressure. Thus, can be expressed by an inherent characteristics G_{inh} (effect of connected system not present), leading to an installed characteristic G_{ins} (effect of connected system included). The inherent characteristics can be expressed in linear or equal percentage as:

$$\text{Linear}: G_{inh} = G_o + u(1 - G_o) \tag{4}$$

$$\text{Equal Percentage}: G_{inh} = G_o^{(1-u)} \tag{5}$$

$$G_{ins} = [1 + N(\frac{1}{G_{inh}^2} - 1)]^{-1/2} \tag{6}$$

Where, G_o is the let-by (can be obtained from manufacturer), N is the valve authority and u is the stem position.

III. Model Implementation

From the statistics released by the Department for communities and Local Government, one of the common types of house in England is a semi-detached house, which accounts 26 % of the total housing stock [9]. This forms the basis for a case study of two storeys semi-detached house located in Newcastle facing south with three bedrooms and floor area of 47 m^2, as shown in figure 2, is considered. It is assumed that the double glazed house is occupied by medium size family of four members: two middle age adults (working full time) and two children (going school). And has two active occupancy (when occupant is awake) pattern for weekdays and weekends as shown in table 1.

The house is divided into three separate zones on the basis of heating requirements. All three zones are heated and controlled. Zone 1 refers to living room and is set to an internal design temperature of 21 °C, zone 2 refers to three bedrooms and is set at 16 °C and zone 3 (referred as balance zone) refers to the remaining parts of the house is set at 18 °C.

In building model, the construction element considered for this case study is different that considered by Gouda [1], the slight change in the ratio of resistance and capacitance is considered than the proposed. The values of resistances and capacitances considered are:

$R_1 = 0.05R_T$; $R_2 = 0.45R_T$; $R_3 = 0.5R_T$ and

$C_1 = 0.05C_T$; $C_2 = 0.95C_T$;

These changes in ratio are due to the consideration of different construction elements for external wall and internal partition then that is considered by Gouda.

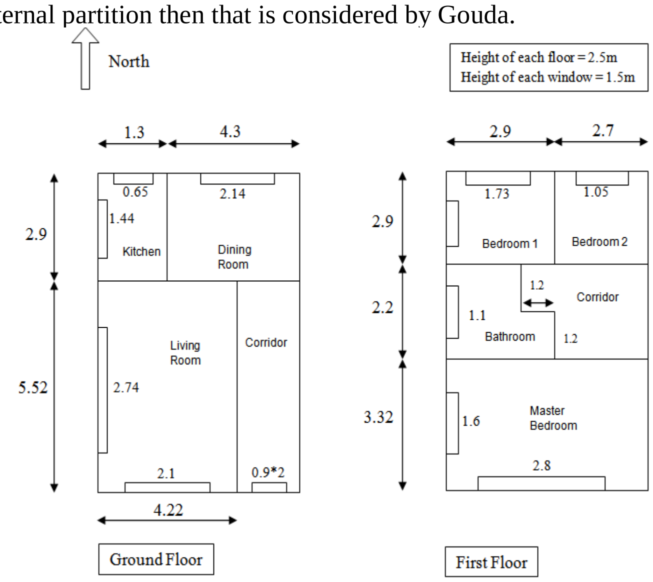

Figure 2: Plan View of house

Table 1: Active Occupancy pattern

Day	Active Occupancy period	
Weekdays (Monday - Friday)	07:00 – 09:00	17:00 – 23:00
Weekends (Saturday & Sunday)	08:00 – 23:00	

The data used for the calculation can be divided into three categories:

- House and heating system – U-values, ventilation rates etc.
- Weather – external temperature, solar radiation, wind speed etc.
- Household variables – heating patterns, water heating, electrical appliances etc.

The data used in this project for the building model construction are from SBEM database [10] (building's energy consumption analysis software developed by BER for Department for Communities and Local Government), whereas the internal gains are calculated using simple formulas given in BREDEM-12 [11].

Figure 3 shows the temperature of the three zones for one week in which day 5 and 6 are weekends. The heating system is controlled on the basis of occupancy pattern and the desired set temperatures. The heating system uses variable flow constant temperature strategy, in which room temperature sensor and the control valve seeks to vary the hot water flow rate into the emitter in response to room temperature to obtain the desired temperature.

Figure 4 shows the amount of heat emitted by the heating system to maintain the desire set temperature. As the set temperature of the living room is the highest (21 °C), the heat emission in the living room is greater than the other Zones. Point to note here is that on day 5 and 6, which are weekends and heating is 'on' all day from morning to night, when solar radiation comes into effect, the room gets heated and heat emission reduces during mid-day. The heat demand for the one winter week of the living room, bedroom and balance zones are 60.2 kWh, 42.54 kWh and 39.5 kWh respectively.

IV. Validation

It is always important to validate the building simulation model developed before the model is to be implemented. There has been much effort done at the International Energy Agency (IEA) [12], the American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) [13] and others to create methodologies, tests and standards to verify the reliability and accuracy of the building models. Judkoff and Neymanrk [12], have proposed three validation methods: Analytical verification, Empirical validation and Comparative testing.

In comparative testing, result from one program is compared to another program. This includes both sensitivity testing and inter- model comparisons. Results from two or more programs are compared (with identical inputs) in inter-model comparison. This method of testing enables inexpensive comparison at different levels of complexity. However, in practice the difficulties in matching the program inputs can lead to significant uncertainty in performing inter-model comparisons.

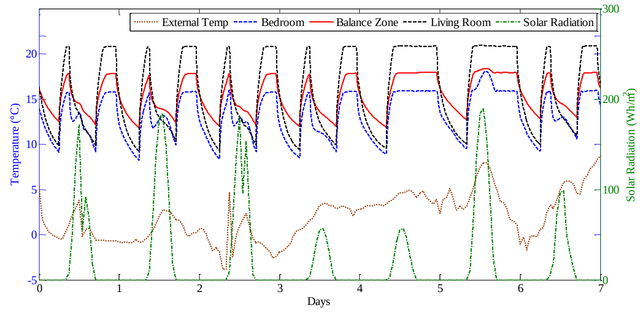

Figure 3: Air Temperature of the Three Zones with Heating

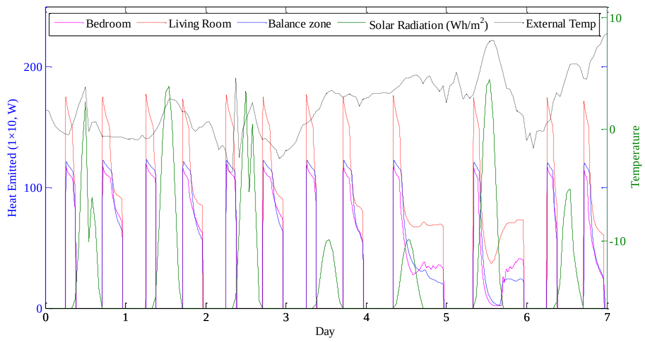

Figure 4: Heat Emitted in Three Zones

Among these testing, inter-program comparative testing is used to validate the developed thermal model of house and as a diagnostic tool to identify the errors associated with the implementation of the model. The results obtained from the model developed in Matlab are compared with the results obtained from the Design Builder software. The outputs obtained from Design Builder are based on detailed sub-hourly simulation time steps using the EnergyPlus simulation as an interface. EnergyPlus has been tested against the IEA Building Energy Simulation Test (IEA BESTest) building load and HVAC tests.

Figure 5 shows the comparison of air temperature of the bedroom obtained from Matlab/Simulink' and Design Builder without a heating system for a whole week. The pattern of air temperature in the bedroom obtained from Simulink seems to resemble that obtained from the Design Builder with the difference in temperature of 1 °C at few points. Similarly, figure 6 shows the comparison of air temperature of the balance zone when the heating system is turned 'on'.

Figures 8 and 9 shows the comparison of air temperature in the living room with and without heating respectively. Figures 5 to 8 show that the patterns of air temperature in the zones are similar. However, the Simulink model consistently under predicts the temperature of living room which is due to the heat coming from ground. In house, living room and bedrooms are considered more important than any other rooms so the comparison graphs of these two zones are only included.

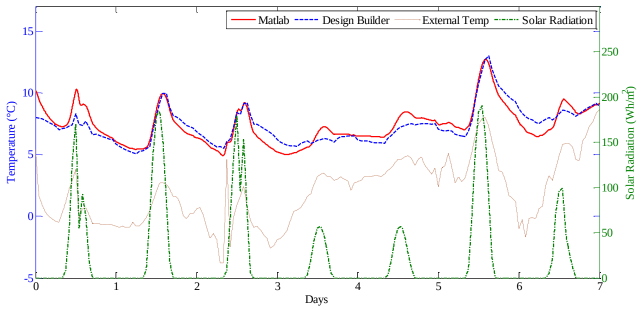

Figure 5: Air Temperature Comparison of Bedroom

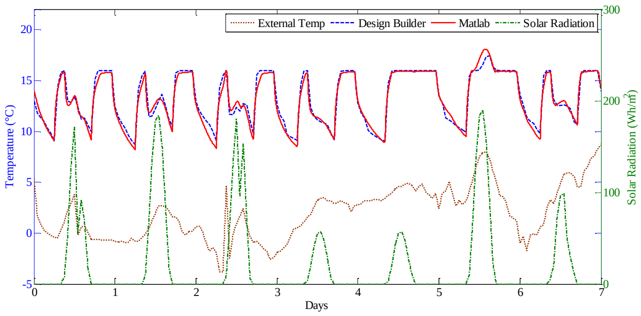

Figure 6: Air Temperature Comparison of Bedroom with Heating

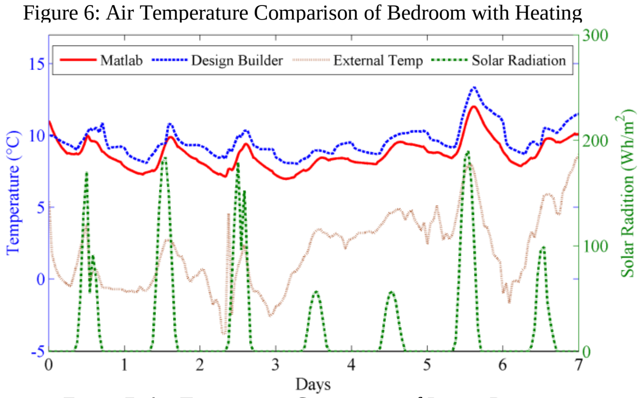

Figure 7: Air Temperature Comparison of Living Room

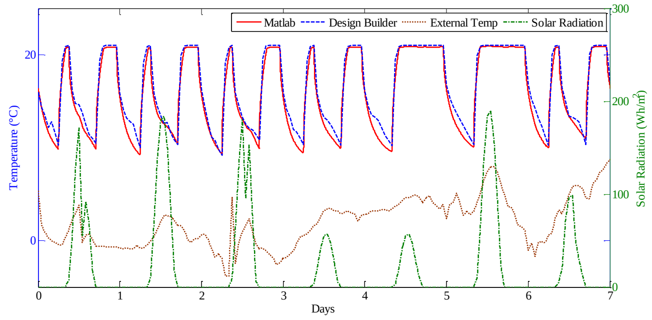

Figure 8: Air Temperature Comparison of Living Room with Heating

V. Conclusion

The simple approach to model the elements of building envelop and heating system has been investigated using Simulink in the Matlab environment. A control strategy developed to obtain the desired temperature in different zones of house has been achieved and tested against IEA Building Energy Simulation Test (IEA BESTest) software.

Using these models, thermal model of any building type with different insulation (U-values) can be modelled and its space heating energy demand can be calculated and thus the carbon emission. Analysis could also be done with different insulations in the building for the reduction of carbon emission from the building i.e. towards low carbon houses. Analysis with different level of comfort requirement in the house which can be fixed over a year or change according to the change in outside temperature could also be done.

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