BUILDINGS THERMAL MODELING

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Abstract. Energy consumption reduction in the buildings sector represents a socio economical, technological and environmental preoccupation which justifies advanced scientific research. These aspects promote the use of different models, such as mathematical models, thermal, electrical, analogy, etc. in order to describe the thermal behaviour of buildings and to evaluate energy consumption in buildings. In order to obtain a better durability in terms of increasing energy efficiency in buildings is useful to use analogies between thermal and electrical models and methods. This analogy is the most important objective for smart grid technologies. However, it is important to consider the relationship between all the phenomena of heat transfer, heat storage and variation in demand for cooling and heating of buildings for better energy consumption estimate.

The work is focused on presenting some mathematical and thermal models of building elements and their analogies with electric circuits' elements. As an application is presented a mathematical model (analytical) and physically in order to reproduce the behaviour of the indoor and walls temperature for a specific period of time for a heated room based on fundamental laws of thermodynamics, heat transfer and variables thermo-physical using the program Matlab.

Keywords: buildings, thermal models, electrical analogy model, thermodynamics.

1. INTRODUCTION

Mathematical description of building systems is complex because several non-linearity and uncertainties, such as coefficients of conduction, convection and radiation properties of materials, climate issues, the effects of solar radiation modelling HVAC systems and technical aspects of the building in the daily program of its inhabitants, the use of light and electrical equipment [8].

In the early lifetime of a building the disagreements between estimated and used energy might be examined, especially if legal actions are taken against the consultants. Later, it can be of interest to use calculations to check the operation of the building, energy retrofitting may be considered. All these situations require accurate calculation methods.

At the early layout stage, the builder and the architect may need some basic ideas of the thermal behaviour of the building. At this stage, very few data about the building may exist, thus simplified calculations methods may or have to be used.

During the design of a building, more and more data are available, thus the engineers are able to perform more and more sophisticated calculations. In the final design stage, the HVAC consultant must be sure that he can meet the builders requirements abut indoor climate and energy consumption, thus proper calculation methods are required.

The need to estimate indoor temperatures, heating or cooling load and energy requirements for buildings arises in many stages of a buildings life cycle [1].

Reducing and optimization of the energy consumption in the residential sector is an important issue in the context of the global warming effect. It is important the modelling and simulation of the houses (thermal, appliances, lighting, comfort, etc.) and optimization of the energy consumption.

The DEHEMS project (DEHEMS, 2010) proposes a low budget optimization of the energy consumption in current households. There are several important aspects which have to be taken into consideration and can lead to the reduction of the energy consumption: thermal model; experimental identification; modelling of HVAC systems; environment model, solar radiation and temperature, occupants; including of the electrical appliances in the model; indoor comfort, thermal comfort, visual comfort, indoor air quality; the changing of the user behaviour [2].

2. GENERAL CONVERSION OF THERMAL MODEL INTO ELECTRICAL MODEL

Converting different types of systems and models into electrical circuits is an idea that has been used for a long time, due to the ubiquitous nature of electrical circuits, as previously mentioned. Mechanical systems, due to their typically linear nature, are one class where these transformations have been successfully used [4].

While many thermal models have been transformed into electrical equivalents, there has been little research on the relation between physical parameters of a building and their electrical parameter equivalents.

2.1. Basic thermal system

The basic components and respective parameters of a thermal system are the following, with the symbols for the parameters in reference to any thermal system considered:

• Heat source, quantified by heat source Q.

• Thermal resistor, quantified by resistance R.

• Thermal capacitor, quantified by thermal capacitance C and temperature T.

The basic components and respective parameters of an electrical circuit are the following, with the symbols for the parameters:

• Voltage or current source, quantified by source V.

• Electrical inductor, quantified by inductance L.

• Electrical resistor, quantified by electrical resistance R.

• Electrical capacitor, quantified by electrical capacitance C.

The basic components of a thermal system are converted to the basic components of an electrical circuit as follows [3]:

• A heat source becomes a current source, with a heat rate quantity, measured in Watts, equivalent to a current quantity, measured in Amperes.

• An outside temperature, measured in degrees Celsius, becomes a voltage source, measured in Volts.

• A thermal resistor and thermal resistance quantity, measured in m^2K/W, becomes an electrical resistor and electrical resistance quantity, measured in Ω, respectively.

• A thermal capacitor and thermal capacitance quantity, measured in Joules per degree Celsius, becomes an electrical capacitor and electrical capacitance quantity, measured in Farads, respectively.

• There is no component and respective parameter in the thermal system diagram that corresponds to an inductor and the inductance, respectively. As will be seen, this will not present a challenge to achieving the objectives of using an equivalent electrical circuit model.

The models presented below, namely the use of suitable thermal modelling method of building tires, simplify and enable a reasonable accuracy of analyzed patterns. So, once the thermal model is simplified, the solving time is also reduced, so that the analytical solution that is intended to be determined will be achieved quite quickly and the results ate easy to be verified.

Another interesting aspect of the modelling by means of thermal networks is active elements, which are referred to as potential sources of heat and temperature.

The heat sources are represented by current sources the specific electrical circuits. Each node of thermal masses characteristic buildings involves a potential difference of temperatures. The outside temperature of the building can be expressed by means of a voltage source. Temperatures inside/outside the building envelope characteristic corresponding power supply circuits.

The following paragraph refers to a number of examples on modelling elements of the building component systems.

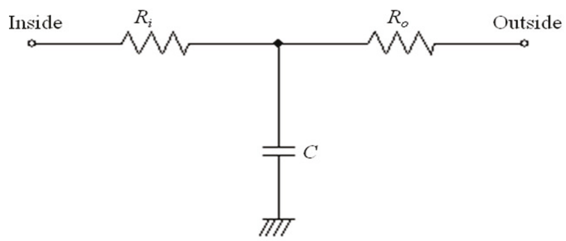

Fig. 1.The first order RC model for a multilayer wall

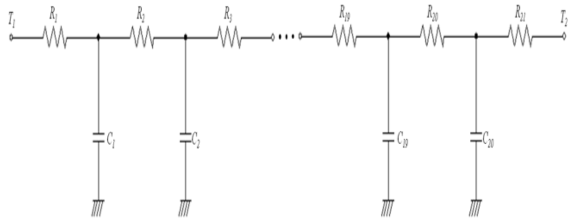

Fig. 2. The higher-order RC model for multilayer wall

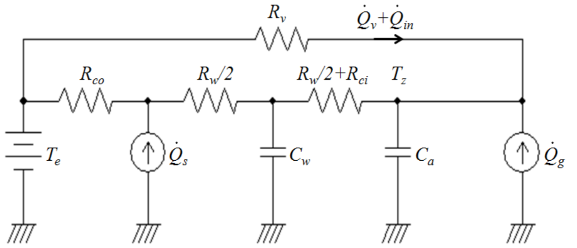

Fig. 3. Simplified thermal model of building multiple sources of heat

3. THERMAL MODEL OF QUASI-ADIABATIC ROOM

This section presents a methodology for designing thermal models for different building elements and identifying their corresponding thermal parameters. Based on the first law of thermodynamics, we suggest lumped RC parameter circuits by using the thermal-electrical analogy, then, the parameter identification methods are presented [6].

3.1. Heat Balance Equation. Simple Model [6]

We consider a single zone model with an electrical power source (fig.4). The heat balance equation is deduced by the first principle of thermodynamics. It is simplified into (1) for a quasi-adiabatic room. It can be also expressed as (2), [6].

The heat balance of the quasi-adiabatic room:

$$\dot{Q}_{aplliance}(t) = \dot{Q}_{envelope}(t) + \frac{dU_{stored}}{dt} \tag{1}$$

The heat gain from appliance is:

$$\dot{Q}_{aplliance}(t) = \dot{Q}_{envelope}(t) + C_{th} \cdot \frac{dT_i(t)}{dt} \tag{2}$$

where C_{th} [J/°C] is the global thermal capacitance of the test room and is the product of the specific heat capacity [J/(kg·°C)] and the mass of the room [kg]. T_i is the indoor temperature of the room [°C].

The heat loss through envelopes of the room, $\dot{Q}_{envelope}(t)$ [W] is:

$$\dot{Q}_{envelope}(t) = \frac{1}{R_{th}} \cdot \left(T_i(t) - T_e(t)\right) \tag{3}$$

where R_{th} is the global thermal resistance of the room [m^2°C/W], T_e is the exterior temperature of the room.

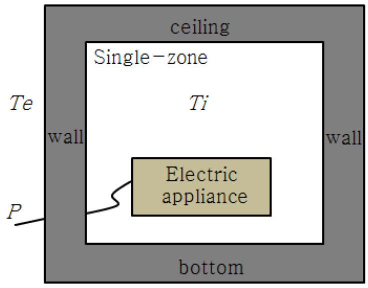

Fig. 4. A single zone model with an electrical power source P, [6]

The indoor temperature can be obtained from (2) - (3). It results (4) when $\dot{Q}_{appliance}(t)$ and $T_e(t)$ are constant.

$$T_i(t) = R_{th} \cdot \dot{Q}_{appliance}(t) + T_e(t) + (T_0 - T_e(0)) - R_{th} \cdot \dot{Q}_{appliance}(0) \cdot e^{-t/\tau_{th}} \quad (4)$$

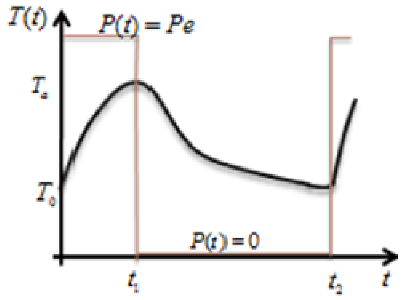

Fig. 5. Example of indoor temperature T(t) and electrical power source profile P(t), [6]

The particular case of no heating period is as following when $T_e(t)= T_e(0)$=constant.

$$T_i(t) = T_e(t) + (T_0 - T_e(0)) \cdot e^{-t/\tau_{th}} \quad (5)$$

where τ ($=R_{th} \cdot C_{th}$) is the time constant of the room [s];

$T_e(0)$ is the initial outdoor air temperature [°C];

T_0 is the initial indoor air temperature [°C], and $\dot{Q}_{appliance}(0)$ is the initial power consumption of the appliance [W].

Equation (4) shows a general equation of the indoor temperature.

Equations (4) and (5) indicate the indoor air temperature $T_i(t)$ when electrical power source $\dot{Q}_{appliance}(t)$ is enabled and disabled, respectively [6].

3.2. Heat balance equation. Complex Model [6]

More complex models of the room can be developed using the heat balance equation. If higher numbers of building elements are modelled, the order, the complexity and the accuracy of the models become higher, but computational efficiency is lower than the case of the simplified building model. The derived heat balance equation for a complex model which consists of m elements is given by (6).

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \quad (6)$$

where

$$x = [T_m \quad T_{m-1} \quad T_{m-2} \quad \ldots \quad T_1]^T \quad (7)$$

$$u = [\Phi_m \quad \Phi_{m-1} \quad \Phi_{m-2} \quad \ldots \quad \Phi_1 \quad T_0]^T \quad (8)$$

$$A = \begin{bmatrix} \frac{1}{R_m C_m} & 0 & 0 & 0 \ldots & 0 & 0 \\ \frac{1}{R_m C_{m-1}} & -\left(\frac{1}{R_m}+\frac{1}{R_{m-1}}\right)\cdot\frac{1}{C_{m-1}} & 0 & 0 \ldots & 0 & 0 \\ 0 & \frac{1}{R_{m-1} C_{m-2}} & -\left(\frac{1}{R_{m-1}}+\frac{1}{R_{m-2}}\right)\cdot\frac{1}{C_{m-2}} & 0 \ldots & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots \ldots & \ldots & \ldots \\ 0 & 0 & 0 & 0 \ldots & \frac{1}{R_2 C_1} & -\left(\frac{1}{R_2}+\frac{1}{R_1}\right)\cdot\frac{1}{C_1} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{C_m} & 0 & 0 & 0 & \ldots & 0 & \frac{1}{R_m C_m} \\ 0 & \frac{1}{C_{m-1}} & 0 & 0 & \ldots & 0 & \frac{1}{R_{m-1} C_{m-1}} \\ 0 & 0 & -\frac{1}{C_{m-2}} & 0 & \ldots & 0 & \frac{1}{R_{m-2} C_{m-2}} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & 0 & \ldots & \frac{1}{C_1} & \frac{1}{R_1 C_1} \end{bmatrix}$$

where x is the state vector (vector of internal temperature nodes [°C]), u is the input vector (internal heat gains [W] and outdoor temperature [°C]), y is the output vector (measured temperature [°C]). A, B, C and D are the matrices of the model. They depend on thermal resistance R_i [m^2°C/W], and thermal capacitance C_j [J/°C].

The indexes m and n are respectively the number of the temperature nodes and the number of the considered heat sources, respectively [6].

4. ANALYTICAL SOLUTION OF INDOOR TEMPERATURE

Equations (2) - (4) are deduced as below:

$$C_{th}\frac{dT_i(t)}{dt} = \dot{Q}_{appliance}(t) - \frac{1}{R_{th}}(T_i(t) - T_e(t)) \quad (9)$$

The general solution of (9) is expressed by:

$$T_i(t) = A \cdot e^{-t/\tau_{th}} \quad (10)$$

where τ_{th} is the thermal time constant of the room which is the product of global thermal resistance and capacitance, [sec] [6].

The particular solution of (9) is derived as follows if $\dot{Q}_{appliance}(t)$ and $T_e(t)$ are constant:

$$C_{th}\left(A^{'}\cdot e^{-t/\tau_{th}}-\frac{A}{\tau}\cdot e^{-t/\tau_{th}}\right)+\frac{A}{R_{th}}\cdot e^{-t/\tau_{th}}= =\dot{Q}_{appliance}(t)+\frac{1}{R_{th}}\cdot T_e(t) \quad (11)$$

$$\left(A^{'}\cdot e^{-t/\tau_{th}}-\frac{A}{\tau}\cdot e^{-t/\tau_{th}}\right)+\frac{A}{\tau_{th}}\cdot e^{-t/\tau_{th}}= =\frac{\dot{Q}_{appliance}(t)}{C_{th}}+\frac{1}{\tau_{th}}\cdot T_e(t) \quad (12)$$

$$A^{'}\cdot e^{-t/\tau_{th}}=\frac{1}{\tau_{th}}\left(R_{th}\cdot\dot{Q}_{appliance}(t)+T_e(t)\right) \quad (13)$$

$$A^{'}=\frac{1}{\tau_{th}}\left(R_{th}\cdot\dot{Q}_{appliance}(t)+T_e(t)\right)\cdot e^{t/\tau_h} \quad (14)$$

$$A=\left(R_{th}\cdot\dot{Q}_{appliance}(t)+T_e(t)\right)\cdot e^{t/\tau_h}+B \quad (15)$$

Consequently,

$$T_i(t)=\left(\left(R_{th}\cdot\dot{Q}_{appliance}(t)+T_e(t)\right)\cdot e^{t/\tau_h}+B\right)\cdot e^{-t/\tau_h} \quad (16)$$

the coefficient B is determined by using the initial condition of temperature, [6]:

$$T_0=T_i(t=0)=T_e(t=0)=\text{constant} \quad (17)$$

Then, T_i at t=0 is given by:

$$T_i(t=0)=T_0=\left(R_{th}\cdot\dot{Q}_{appliance}(0)+T_e(0)\right)+B \quad (18)$$

Therefore,

$$B=T_0-\left(R_{th}\cdot\dot{Q}_{appliance}(0)+T_e(0)\right) \quad (19)$$

As a result, the analytical solution of (9) is defined as:

$$T_i(t)=R_{th}\cdot\dot{Q}_{appliance}(t)+T_e(t)+(T_0-T_e(0))- -R_{th}\cdot\dot{Q}_{appliance}(0)\cdot e^{-t/\tau_{th}} \quad (20)$$

The particular case of no heating regime is given by, [6]:

$$T_i(t)=T_e(t)+(T_0-T_e(0))\cdot e^{-t/\tau_{th}} \quad (21)$$

5. CALCULATION EXAMPLE

5.1. Modeling of Thermal Systems

Thermal systems are encountered in chemical processes like heating, cooling, and air conditioning systems, power plants, etc.

Thermal systems have two basic components: thermal resistance and thermal capacitance. Thermal resistance is similar to the resistance in electrical circuits. Similarly, thermal capacitance is similar to the capacitance in electrical circuits. The across variable, which is measured across an element, is the temperature, and the through variable is the heat flow rate. In thermal systems there is no concept of inductance or inertance. Furthermore, the product of the across variable and the through variable is not equal to power [11].

The mathematical modelling of thermal systems is usually complex because of the complex distribution of the temperature. Simple approximate models can, however, be derived for the systems commonly used in practice [11].

Thermal resistance R is the resistance offered to the heat flow, and is defined as:

$$R=\frac{T_2-T_1}{q} \quad (22)$$

where T_1 and T_2 are the temperatures; q is the heat flow rate.

Thermal capacitance is a measure of the energy storage in a thermal system. If q_1 is the heat flowing into a body and q_2 is the heat flowing out then the difference $q_2 - q_1$ is stored by the body, and we can write [11]:

$$q_2-q_1=mc\cdot\frac{dT}{dt} \quad (23)$$

If we let the heat capacity denoted by C, then:

$$q_2-q_1=C\frac{dT}{dt} \quad (24)$$

where: C = mc, m is the mass, c is the specific heat capacity of the body [7].

5.2. Case study

The physical model used to reproduce the behaviour of the indoor temperature is based on the fundamental laws of thermodynamics, heat transfer, and thermo-physical variables.

In the fig. 6 it is presented the studied room heated with an electric heater. Fig. 7 presents the analogue electric circuit for the study room.

The room is considered as a black-box, and the parameters are in generally adjusted automatically. Therefore, black-box models are used especially for errors detection not for optimization process. Their advantage is the rapid and automated identification of outputs of thermal energy building consumption. With respect to the model internal structure of black-box models it can be static and dynamic, linear and nonlinear models, just as the white-box models.

The structure depends on the relationships between the input and output data. Depending on these relationships, various black-box methods for estimating the parameters (calibration) are available.

In thermal modelling of buildings, it is reasonable to combine the relative strengths of black-box coming from the statistical analysis with the white-box strengths based on physical interpretation [9] [10] in order to obtain a hybrid model. In that sense, the standard “grey-box” approach is based on both, a statistical method and physical properties that meets the physical fundamental principles [7].

The inside of the room is at temperature T_r and the walls are assumed to be at temperature T_w.

Considering the outside temperature is T_e, it was developed a model of the system to show the relationship between the supplied heat q and the room temperature T_r.

The heat flow from inside the room to the walls is:

$$q_{rw} = \frac{T_r - T_w}{Rr} \qquad (25)$$

where R_r is the thermal resistance of the room.

Similarly, the heat flow from the walls to the outside is:

$$q_{we} = \frac{T_w - T_e}{R_w} \qquad (26)$$

where R_w is the thermal resistance of the walls.

Heating equation may be written as, [11]:

$$q - q_{rw} = C_1 \cdot \frac{dT_r}{dt} \qquad (27)$$

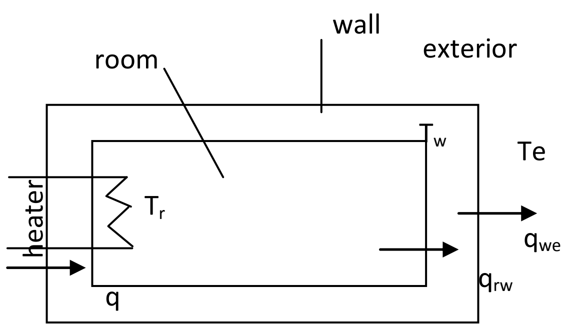

Fig.6. Scheme of the studied room, [7]

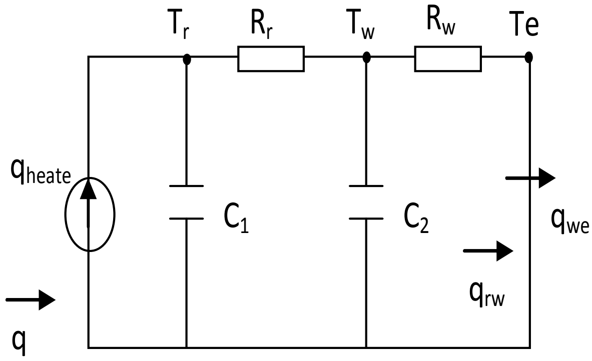

Fig.7. Electrical circuit of the analysed room

where q is the heat flow rate from heater:

$$q - \frac{T_r - T_w}{R_r} = C_1 \cdot \frac{dT_r}{dt} \qquad (28)$$

or

$$C_1 \dot{T}_r + \frac{T_r - T_w}{R_r} = q \qquad (29)$$

Heat equation for

$$q_{rw} - q_{we} = C_2 \cdot \frac{dT_w}{dt} \qquad (30)$$

$$\frac{T_r - T_w}{R_r} - \frac{T_w - T_e}{R_w} = C_2 \cdot \frac{dT_w}{dt} \qquad (31)$$

Or

$$C_2 \cdot \dot{T}_w - \frac{T_{rw}}{R_r} + \left(\frac{1}{R_r} + \frac{1}{R_w}\right) \cdot T_w = \frac{T_e}{R_w} \qquad (32)$$

The system thermal behaviour can be written in matrix form as [11]:

$$\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{T}_r \\ \dot{T}_w \end{bmatrix} + \begin{bmatrix} \frac{1}{R_r} & -\frac{1}{R_r} \\ -\frac{1}{R_r} & \frac{1}{R_r} + \frac{1}{R_w} \end{bmatrix} \cdot \begin{bmatrix} T_r \\ T_w \end{bmatrix} = \begin{bmatrix} q \\ \frac{T_e}{R_w} \end{bmatrix} \qquad (33)$$

or

$$\begin{bmatrix} \dot{T}_r \\ \dot{T}_w \end{bmatrix} = \begin{bmatrix} \frac{q}{C_1} \\ \frac{T_e}{C_2 R_w} \end{bmatrix} - \begin{bmatrix} \frac{1}{C_1 R_r} & -\frac{1}{C_1 R_r} \\ -\frac{1}{C_2 R_r} & \frac{1}{C_2 R_r} + \frac{1}{C_2 R_w} \end{bmatrix} \cdot \begin{bmatrix} T_r \\ T_w \end{bmatrix} \qquad (34)$$

6. SIMULATIONS AND RESULTS

As an example for our simulation study it is considered a room heated by a heater, fig. 6. In order to simulate de indoor temperature of the room and the wall temperature variation in time, it will be taken into account several simplifying assumptions:

-the walls of the room are made from the following layers (starting from interior) plaster board, hard concrete and plaster board;

-the convective heat exchange, on both the sides of the walls, has been considered as constant, and equal to 8 W/m^2K;

-internal loads are considered very small;

-the internal mass is considered to be light;

-the simulation is performed for the stationary state case;

Case 1: We consider the following values for: thermal constants, C_1=0.5, C_2=1.5, thermal resistance of the room, R_r=1.2, wall R_w=2.3, and temperature outdoor, T_e=0, room temperature T_r=20 and wall temperature T_w =10.

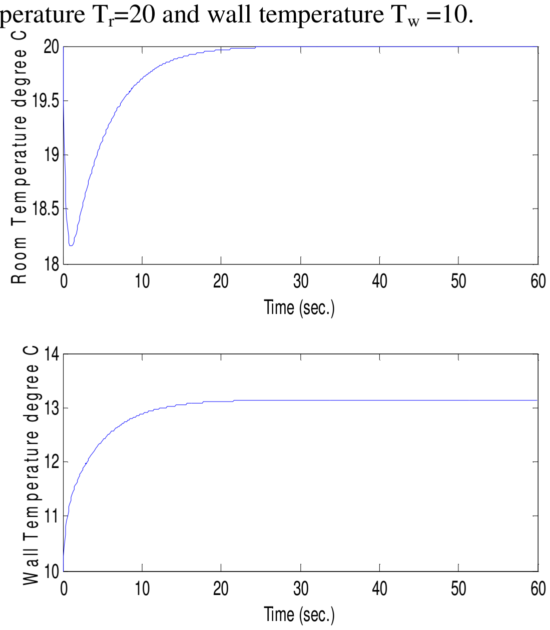

Fig. 8. Simulation case for 60 minutes, 1 hour

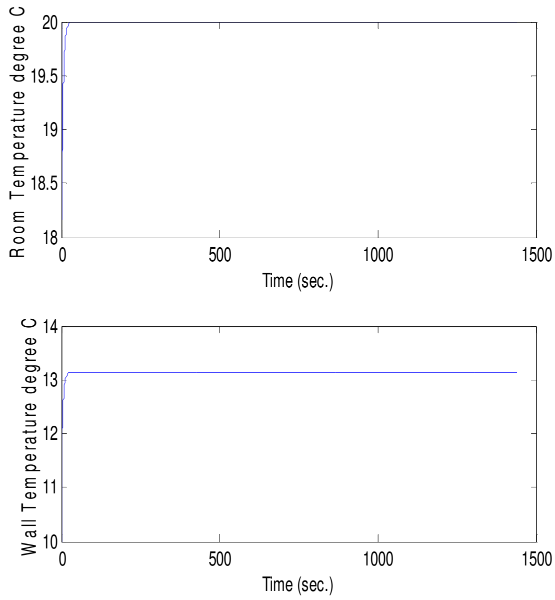

Fig.9.Simulation case for 1440 minutes, 24 hours

Case 2: We consider the following values for: thermal constants, C_1=1, C_2=1.5, thermal resistance of the room, R_r=0.5, wall R_w=3.5, and temperature outdoor, T_e=5, room temperature T_r=20 and wall temperature T_w =10.

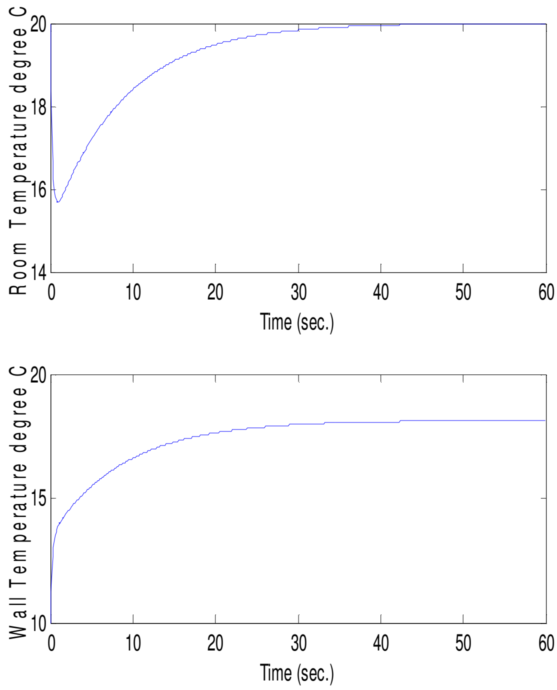

Fig. 10. Simulation case for 60 minutes, 1 hour

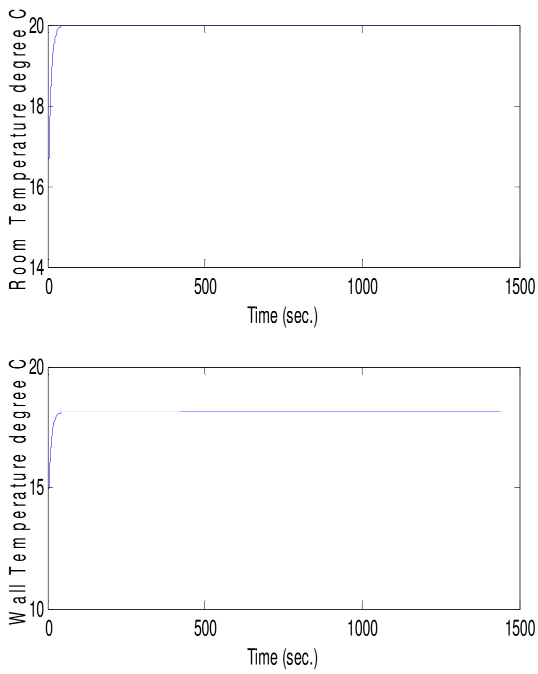

Fig.11.Simulation case for 1440 minutes, 24 hours

7. CONCLUSIONS

Fig. 8 and 9 present the simulation for the case 1, for 1 hour, 60 minutes, respectively for one day, 24 hours, 1440 minutes.

Fig. 10 and 11 present the simulation for the case 2, for the same period of time as it is simulated in the first case.

It can be observed that the room temperature has a low drop, for both cases, in the first 2-3 seconds, and after that it is growing, and finally is stabilized to the input value, T_r=20°C.

The room temperature, for the first case, drops from the input value T_r =20°C to T_r =18.1°C, in first 2-3 seconds, taking into account that the heat flow rate from heater is 5.7143 W, and the outdoor temperature is 0°C.

In the case 2, the room temperature drops from the input value T_r =20°C to T_r =15.9°C, in first 2-3 seconds, taking into account that the heat flow rate from heater is 3.75 W, and the outdoor temperature is 5°C.

As a final conclusion, it results that the indoor temperature is affected more by heat gains from electrical appliances, lighting, occupancy and sun, then than by the outdoor temperature.

The temperature of the wall is affected by the behaviour of indoor temperature. This means that, the outside temperature does not influence much the behaviour of indoor temperature because the wall thermodynamically separates the interior surface from the exterior.

If we consider a large thickness of insulation on the outside layer of the wall, this will works as almost adiabatic condition for both internal and external layers.

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