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The Role of Thermal Mass in a U.S. Prototypical Residential House

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Abstract Thermal mass is important for controlling temperature in buildings. This paper systematically investigates the roles of exterior and interior thermal mass (eTM/iTM) in a U.S. prototypical residential house. A resistor-capacitor (RC) model of the house is built in Matlab/Simulink. Simulation results show that, with normal amount of iTM in a wood-envelope house, changing the wood thickness in a reasonable range can keep the operative temperature variation in 2.1-3.4 °C; correspondingly, in a concrete-envelope house, the variation is in 0.9-1.9 °C. With constant envelope total thermal resistance, adequate iTM and sufficient heat exchange rate between iTM and indoor air are both necessary to maintain the operative temperature variation in a small range. It shows that concrete as iTM has a better control on operative temperature than wood, and thus from the point of view of heat storage, concrete is better than wood as thermal mass due to its larger heat capacity.

Keywords: *building energy modeling, RC model, thermal mass, residential house, heat transfer, heat storage*

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1. Introduction

Thermal mass "has the ability to absorb and store heat energy during a warm period of heating and to release heat energy during a cool period later." [1] Thermal mass is important for controlling indoor temperatures in buildings. Building thermal mass can be classified as exterior (envelope) thermal mass (eTM) and interior thermal mass (iTM) based on its location and function. On the use of thermal mass in building applications, a large volume of architectural literature exists. Some researchers used tests and measurements to investigate building thermal mass [2,3], while others used numerical methods [4,5], in which lumped method is commonly applied to thermal mass calculations. Lumped method supposes that the thermal conduction process within materials is much faster than thermal convection at material surfaces, which is improper in building thermal mass calculations under most circumstances. [1] In order to find details of heat transfer in thermal mass, two papers [1,6] investigated the dynamic heat transfer performance of both interior and exterior planar thermal mass subject to periodic heating and cooling. However, in these papers the indoor air temperature acted as an input parameter rather than as an output result.

In this paper, a resistor-capacitor (RC) model is built in Matlab/Simulink to systematically investigate the role of thermal mass in a U.S. prototypical residential house. In Section 2, the schematics of the prototypical residential house are presented, including the dimensions, the configurations, the envelope, the energy gains and the interior thermal mass. In Section 3, the detailed RC model of the house is built in Matlab/Simulink. The exterior thermal mass (eTM) and the interior thermal mass (iTM) in the house are investigated using the RC model in Section 4 and Section 5, respectively. Brief conclusion is summarized in Section 6.

2. A U.S. Prototypical Residential House and Its Thermal Environment

For simplicity, we consider a model of a building system consisting of the following elements: (1) building envelope (walls, floor, ceiling/roof, windows and doors), (2) interior thermal mass (iTM), (3) indoor air, (4) solar energy input, and (5) internal heat gains. The envelope is defined by its thermal resistance R_{env} (K/W) and heat capacity C_{env} (J/K); the iTM is by its thermal resistance R_{iTM} (K/W), heat capacity C_{iTM} (J/K), thickness L_{iTM} (m), surface area A_{iTM} (m^2), and the heat transfer coefficient h (W/m^2 K) between the iTM and the indoor air; the indoor air is by its heat capacity C_{air} (J/K), volume V_{air} (m^3) and temperature T_{in} (K or °C).

2.1. Dimensions And Configurations

The investigated house is a one-story south-facing residential house, which has a living room, a dining room, a kitchen, three bedrooms and two bathrooms, as shown in Figure 1. The total floor area is 214.6 m^2. The house can be divided into two thermal zones: the living zone (consisting of the living room, the dining room, the kitchen and the two bathrooms) and the bedroom zone (the three bedrooms). Each zone is maintained at similar temperature and humidity conditions throughout the year.

In the house there is one exterior south-facing wood door with dimensions of 0.91 m × 2.13 m. The door is modeled as rigid insulation between two 0.013 m SPF wood layers [7]. A thermal resistance of 1.02 m^2 K/W is used for the door [7]. The house has seven windows in the living zone and six windows in the bedroom zone. The dimensions of the windows are 1.52 m × 2.13 m. And thus the total area of the windows is 42.27 m^2 and the area ratio of the glazing to the floor is 19.7%, which is in the range of design recommendations of passive solar glazing (15%~29% [8]). All the windows are modeled as "double glazing (e = 0.05 on surface 2 or 3), 12.7 mm air space, wood/vinyl frame" operable windows, and thermal resistance of this kind of window is 0.53 m^2 K/W [9]. As the exterior walls, the interior walls, the roof and the floor have a great amount of thermal mass, these components will be varied and the selection will be given in Section 4 and Section 5.

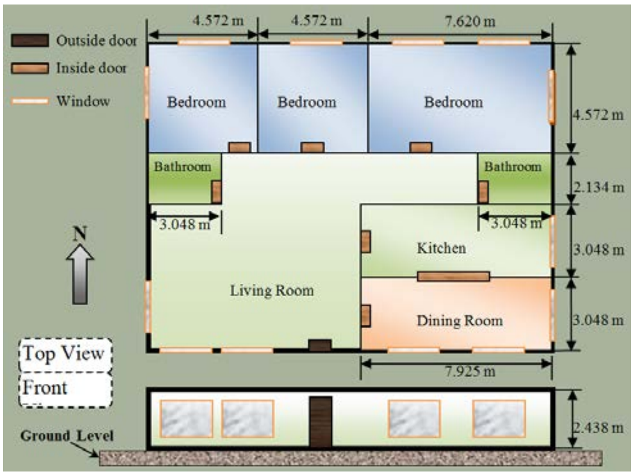

Figure 1. Schematic of the prototypical residential house

2.2. Envelope Thermal Resistance

The overall thermal resistance of the building envelope contains two parts: the thermal resistances of building materials and the surface air film resistances (interior R_i and exterior R_o). There are eight Climate Zones in the United States and the insulation recommendations of residential buildings can be found in Ref. [8]. According to Chapter 26 in Ref. [10], for non-reflective surfaces with emittance ε = 0.90, standardized inside surface resistances due to air films are from 0.11 to 0.16 m^2 K/W. The range of the inside surface thermal resistance of windows is from 0.13 to 0.15 m^2 K/W converted according to Chapter 15 in Ref. [10]. In this paper, the value 0.14 m^2 K/W is chosen for simplicity. For outside surfaces, the surface resistance is 0.044 m^2 K/W in summer or 0.030 m^2 K/W in winter [10]. The average value 0.037 m^2 K/W is used here.

2.3. Thermal Resistance due to Ventilation and Infiltration

Air exchange of outdoor air and indoor air has two classifications [11]: ventilation, which is "the intentional introduction of air from the outside into a building," and infiltration or exfiltration, which is "the uncontrolled flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress." According to Ref. [8], the heat gain/loss of building floor area due to ventilation/infiltration in the house is selected as 0.50 W/K m^2, which means that the house is a little tight (well-sealed). Therefore, the thermal resistance due to the ventilation and infiltration can be gotten as R_{vi} = 0.009320 K/W, which is parallel to the house envelope thermal resistance R_{env}. The thermal network of the house is shown in Figure 2.

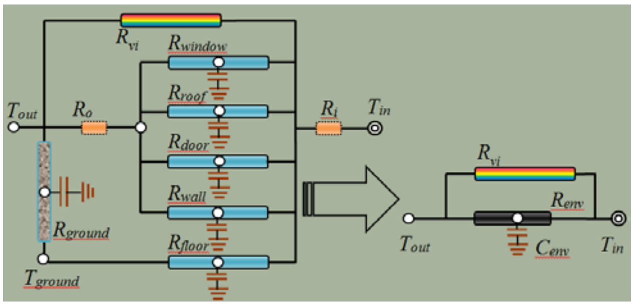

Figure 2. Thermal network of the house

2.4. Solar and Internal Heat Gains

Radiation solar energy input through windows is an important part of building energy gains. The total solar energy input through the windows of the prototypical house is calculated using the method given by Ref. [12]. A program is written in Matlab for calculating the solar irradiance, which is the solar intensity that is incident perpendicular (normal) to one unit area of a plane surface. The total solar irradiance incident upon a flat surface, I_T [W/m^2], is given by

$$I_T = I_b + I_d + I_f \tag{1}$$

where I_b [W/m^2] is the direct beam component of solar irradiance on the tilted plane surface; I_d [W/m^2] is the diffuse component and I_f [W/m^2] is the reflected component.

Since the window type is selected as double glazing with low-E coating, the shading coefficient, C_{sc}, is 0.32~0.60 for this type of windows. Choose C_{sc} = 0.46. In most residential houses, besides using glazing, shading strategies are also used to control solar heat gain to minimize cooling requirements. In Chapter 15 in Ref. [10], many details about shading are given. It points out that "fenestration products fully shaded from the outside reduce solar heat gain by as much as 80%." So assume that 20% solar energy can go into the house, and thus give a coefficient C_{sd} = 0.20. Therefore, on clear days (i.e., cloudless and sunny), the heat flux of solar energy input, q_s'' [W/m^2], can be obtained as

$$q_s'' = C_{sd} C_{sc} (I_b + I_d + I_f) \tag{2}$$

The house location is selected around Stony Brook University, and the solar energy input through windows of the house is shown in Figure 3. Assume that half of the solar energy is put on the floor and the other half is put on one surface of the iTM.

The internal heat gains, which are the heat energy emitted by occupants, lighting, and appliances, contribute a significant amount of heat to the total sensible and latent heat gains in a house. According to Chapter 18 in Ref. [10], the sensible heat and latent heat from occupants are about 75 W and 55 W, respectively. For simplicity, suppose that there are five persons in the house, and during work time (9:00AM to 5:00PM), the occupants are not in the house. From Chapter 4 in Ref. [7], the heat gains from lights and appliances can be calculated. The total internal heat gains are shown in Figure 4.

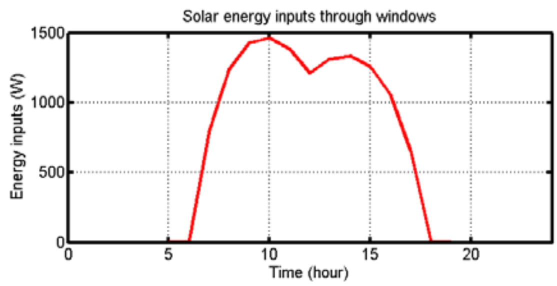

Figure 3. Solar energy input through windows of the house

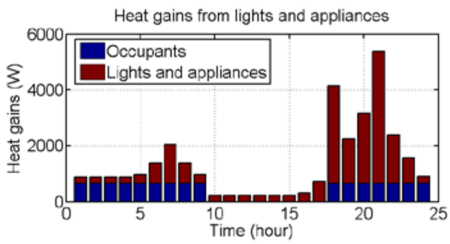

Figure 4. Total internal heat gains of the house

2.5. Interior Thermal Mass (iTM)

In Ref. [7], it is said that iTM can be divided into thermal mass due to interior walls and thermal mass due to furniture. The material composition of the interior walls is "two lays of 0.5″ gypsum separated by 3.5″ of air to represent the standard interior wall construction excluding 2×4 studs at 16″ O.C.". From Figure 1, the length of the interior walls is about 55.2 m. Thus, the total surface area of the interior walls (two sides) is 269 m^2 and the volume is 3.4 m^3. All the furniture is assumed to be composed of wood in Ref. [7]. The furniture specifications in the living and bedroom zones were given in Chapter 4 in Ref. [7]. Thus the total area (two sides) and volume of the furniture in the house are about 274 m^2 and 73.6 m^3, respectively. So the average thickness of iTM due to furniture is about 0.537 m. As the thermal mass due to interior walls is less than 5%, it can be neglected.

3. The House Model In Matlab/Simulink

The thermal network of a building can be modeled by a resistor-capacitor (RC) electric circuit—with various "thermal resistor" *resistance* values, "heat capacity" *capacitance* values, input and output "temperature" *potential* values, and "heat energy gain" *current* values. There is a large volume of literature using the RC model on building energy modeling [13-23]. In this paper, the thermal network of the prototypical residential house is modeled following the RC network treatment developed in previous literature.

The RC model of the residential house is built in Matlab/Simulink, as shown in Figure 5. The units of the symbols in the figure are: T (K or °C), R (K/W), C (J/K), and q (W = J/s). For electric circuit, the corresponding units of the symbols are: U (V), R (Ω=V/A), C (F = C/V), and I (A = C/s). This RC model of the house has components of the house envelope, the solar energy input, the internal heat gains, the iTM, the indoor air, and the outdoor air. Most of the components were described in Section 2. The indoor air temperature, T_{in} (K or °C) is allowed to "float" in this model. The outdoor air temperature, T_{out} (K or °C) is supposed as a sinusoidal function with a period of 24 hours. September 15 is chosen for the calculation. In this month, the average high and low temperatures of the outdoor air are 14 °C and 24 °C, respectively. The sampling time step of the simulation is 10 s.

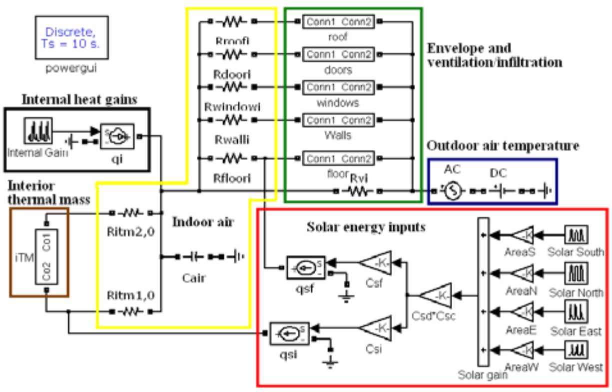

Figure 5. RC model of the house in Matlab/Simulink

Suppose that the house envelope (roof, floor and walls) is made of 25cm-thick wood, and insulations are added to meet the recommendations (Zone 4). The thicknesses of the insulations are: 26.1 cm for roof (R_{roof} = 8.6 m^2 K/W), 9.3 cm for floor (R_{floor} = 4.4 m^2 K/W) and 6.7 cm for walls (R_{wall} = 3.75 m^2 K/W). Simulation results are shown in Figure 6.

From Figure 6(a), we can find: due to smaller thermal resistances of the windows and the door, the temperatures of them (the two solid lines) are much lower than that of floor, roof and walls, and the temperature variations of them are much bigger; the floor temperature (the red dash-dot line) is a little higher in the daytime because of the solar energy input; thanks to the high internal heat gains in the evening time, all the temperatures have two peaks correspondingly. From Figure 6(b), we know: in the nighttime, the indoor air temperature (the black solid line) is lower than the iTM surface temperatures (the other two lines), because heat first losses from the indoor air to the outdoor air through the house envelope and then losses from the iTM to the indoor air; in the daytime, since part of the solar energy input is on the iTM sun-facing surface, the temperature (the red dotted line) is about 0.5 °C higher than that of the iTM shaded surface (the blue dash-dot line); in the evening time, due to the large amount of internal heat gains, the indoor air temperature increases about 1.5 °C, which may cause thermal discomfort in the house.

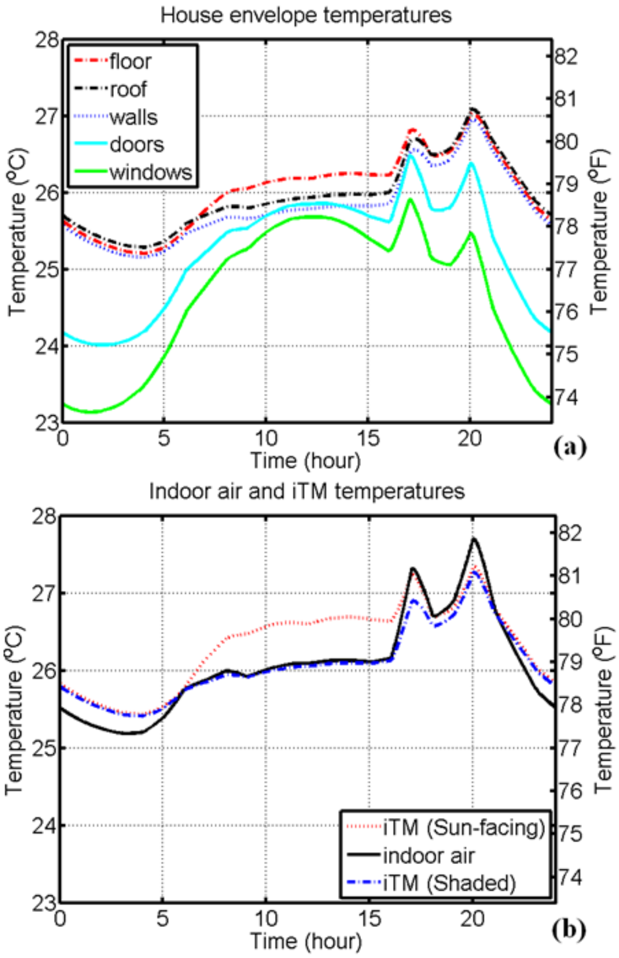

Figure 6. RC model of the health center in Matlab/Simulink

In the chart of the comfort zones [10] specified in ANSI/ASHRAE Standard 55, the temperature on the x-axis is the indoor operative temperature, which "is uniform temperature of a radiantly black enclosure in which an occupant exchanges the same amount of heat by radiation plus convection as in the actual nonuniform environment." [11] Weighted by their respective heat transfer coefficients, the operative temperature T_{op} is defined as the average of the mean radiant temperature (*MRT*) $\overline{T}_r$ [K or °C] and the indoor air temperature T_{in} [10]:

$$T_{op} = \frac{h_r \overline{T}_r + h_c T_{in}}{h_r + h_c} \tag{3}$$

where h_r and h_c are the radiative and convective heat transfer coefficients, respectively.

The mean radiant temperature $\overline{T}_r$ "is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure." [10] A useful simplification is given as [11]:

$$MRT = \overline{T}_r = \frac{A_1 T_1 + A_2 T_2 + \ldots + A_N T_N}{A_1 + A_2 + \ldots + A_N} \tag{4}$$

where $A_1 \ldots A_N$ are areas of the surfaces in an "actual nonuniform enclosure", and $T_1 \ldots T_N$ are the corresponding temperatures of the surfaces.

Eqs. (3) and (4) are used to calculate the operative temperature in this paper.

4. Investigation on Exterior Thermal Mass in the House

In this section, the model developed in Section 3 will be used to investigate the role of eTM (i.e., building envelope) in the prototypical residential house.

The envelope of the house is assumed to be made of three kinds of materials: wood (with low thermal conductivity and small heat capacity), concrete (with high thermal conductivity and large heat capacity), and insulation (with very low thermal conductivity and almost no heat capacity). Main properties of the materials are listed in Table 1.

Table 1. Specifications of building envelope materials

	Conductivity	Capacity	Density	Description
	k (W/m K)	*C* (kJ/kg K)	*ρ* (kg/m^3)	
Wood	0.12	1.382	510	low *k*, small *C*
Concrete	1.90	0.795	2320	high *k*, large *C*
Insulation	0.04	0.000	0	very low *k*, no *C*

4.1. Wood as Exterior Thermal Mass

First consider the house whose envelope is built by wood and insulation. Changing the thicknesses of wood and insulation while keeping the envelope total thermal resistance as a constant, operative temperatures of the wood house are shown in Figure 7.

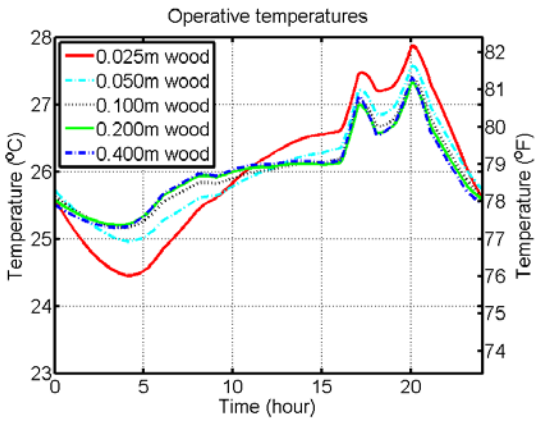

Figure 7. Operative temperatures of the wood house with different wood thicknesses

In Figure 7, the thicknesses of the wood in the envelope are doubled from 0.025 m to 0.400 m. When the wood is thin, the operative temperature variations can be up to 3.4 °C (the red solid line for the 0.025m case); with the increase of the wood thickness, the variations decrease to about 2.1 °C; with carefully observation, the variation in the 0.400m case (the blue dash-dot line) in fact is a little bigger than that in the 0.200m case (the green solid line). The reason is that the maximum heat storage thickness for wood is about 0.162 m according to Refs. [1], [6].

4.2. Concrete as Exterior Thermal Mass

Next consider the house envelope is made of concrete and insulation. The total thermal resistance of the envelope is the same as that of the wood house. The concrete thickness is varied and simulation results are shown in Figure 8.

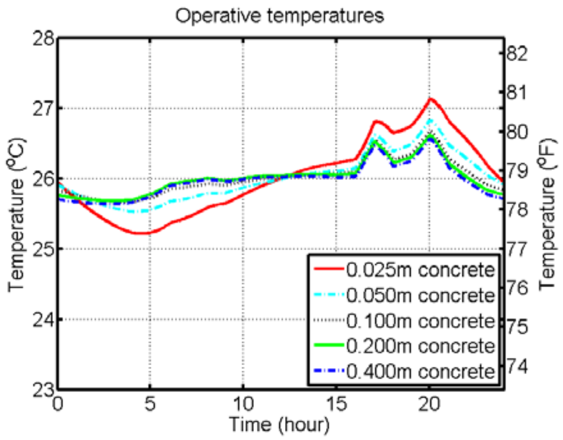

Figure 8. Operative temperatures of the concrete house with different concrete thicknesses

According to Refs. [1,6], the maximum heat storage thickness for concrete is about 0.398 m. Therefore, with the increase of the concrete thickness, the operative temperature variations keep on decreasing from 1.9 °C (the red solid line for the 0.025m case) to 0.9 °C (the blue dash-dot line for the 0.400m case) as shown in Figure 8.

4.3. Comparison Of The Wood House And The Concrete House

As shown in Figure 7 and Figure 8, when the thicknesses of wood and concrete are the same, the operative temperature variations in the concrete house are much smaller than that in the wood house. This is because the heat capacity of concrete is about two times larger than that of wood. From this point of view, concrete is better than wood as building envelope. However, the conclusion in Ref. [6] is opposite: "a wood wall is better than a concrete wall of same thickness as exterior walls in terms of the time-lag effect and the decrement factor".

In fact, these two conclusions are not contradictory. In this paper we mainly consider the heat storage role of wood or concrete, while in the reference the heat transfer role of wood or concrete was mainly considered. In this paper, the envelope total thermal resistance is constant, which means that the insulation is much thicker in the concrete house than in the corresponding wood house. But in Ref. [6], there was only wood or concrete without insulation.

Therefore, concrete is better than wood as building thermal mass (for heat storage consideration), while wood is better than concrete as building structural material (for heat transfer consideration).

5. Investigation on Interior Thermal Mass in the House

Now we will investigate the role of iTM (which is assumed as planar in shape) in the house. The house envelope is assumed to be built by insulation only without thermal mass in order to show the iTM effect more clearly. The insulation thicknesses of the house envelope are: 0.344 m for roof, 0.176 m for floor, and 0.150 m for walls, in order to meet the Climate Zone 4's insulation requirements.

5.1. Lumped Method Is Improper for Interior Thermal Mass Calculations

In Ref. [1], it pointed out "the lumped method, which is used to do interior thermal mass calculation in most papers and software programs, is incorrect under most circumstances." Now, let us first do the calculation using the RC model (the iTM is assumed as wood) built above, and then applying the lumped method in the model, i.e., we neglect the iTM thermal resistances. With the lumped method, the interior temperature is uniform in each thermal mass. The operative temperatures in these two cases are shown in Figure 9. From the figure, it is clear that the temperature variation in the lumped method (the blue dash-dot line) decreases about 3.5 °C compared with that in the RC model (the black solid line), which is 60.6% decrease! Obviously, there is a big error using the lumped method for iTM calculations.

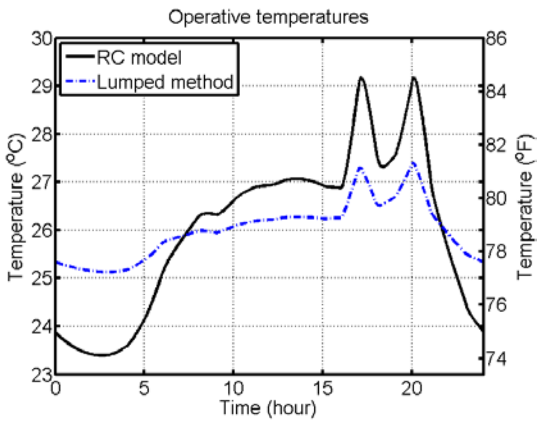

Figure 9. Operative temperatures by using the RC model and the lumped method

5.2. Size of Interior Thermal Mass

Let us first change the iTM size while keeping the heat transfer rate as constant, that is, change the iTM thickness while keeping the iTM surface area and the heat transfer coefficient as constant.

The result of the extreme case with no iTM at all is shown in Figure 10. In this case, the house is empty and the variation of the operative temperature is about 16.4 °C. Although this case may not be real, it gives an intuitive understanding of the crucial role of iTM in buildings.

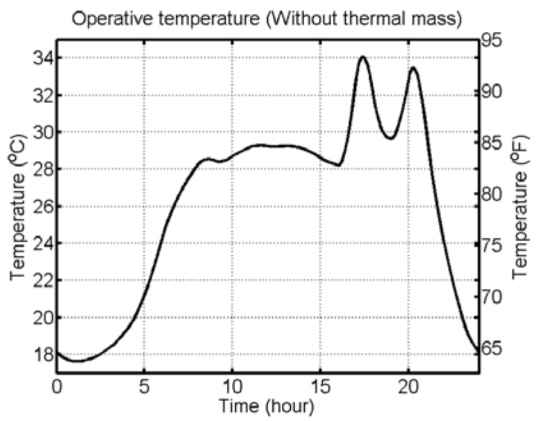

Figure 10. Operative temperature in the extreme case without thermal mass

Simulation results of changing the iTM size are shown in Figure 11. In this figure, the iTM thickness is doubled each step from 0.025 m to 0.400 m. The temperature trends are similar as that in the eTM cases shown in Figure 7: with the increase of the iTM thickness, the temperature variations decrease from about 11.0 °C (the red solid line for the 0.025m case) to 5.3 °C (the green solid line for the 0.200m case); however, the variation increases to 5.6 °C in the 0.400m case (the blue dash-dot line). Therefore, for wood iTM there is no rationale of using thickness greater than the optimal thermal mass thickness, which is about 0.162 m according to Ref. [1].

It is clear that sufficiently large iTM size is necessary to keep the operative temperature varying in a small range, which is crucial for a building with good thermal comfort. However, after a certain thickness of the iTM, heat cannot flow into the deep inside of the iTM and thus the benefit of further increasing the thickness of iTM vanishes.

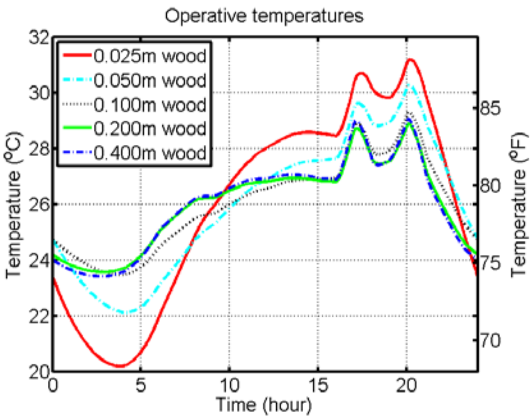

Figure 11. Operative temperatures when changing the iTM size (thickness)

5.3. Heat Transfer Rate between Interior Thermal Mass and Indoor Air

As seen in Section 5.2, the operative temperature variation is still large (more than 5 °C) even when the thermal mass thickness is optimized. Therefore, other efforts still need to be made to reduce the variation. Now let us change the heat transfer rate between the iTM and the indoor air, while keeping the iTM size as constant.

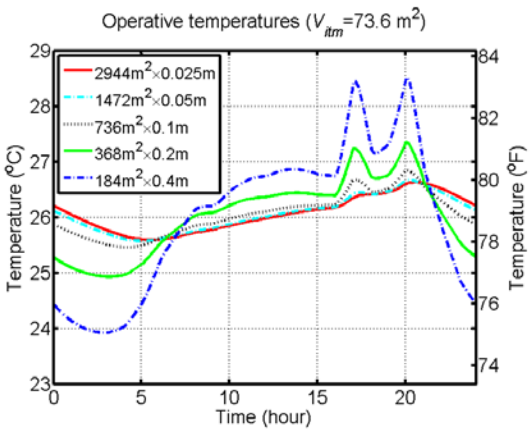

Figure 12. Operative temperatures of changing the heat transfer rate between the iTM and the indoor air

The heat transfer coefficient is a little hard to be changed. For example, a fan blowing at the iTM surface can increase the coefficient, but it is unsuitable from the considerations of energy saving and human thermal comfort. So we will vary the heat transfer rate by varying the iTM surface area. Here, the iTM volume will be kept as constant, and thus the iTM thickness will decrease with the increase of the iTM surface area. Simulation results are shown in Figure 12. With the increase of the heat transfer rate, the temperature variations decrease from 4.6 °C (the blue dash-dot line for the 184m^2×0.4m case) to 1.0 °C (the red solid line for the 2944m^2×0.025m case).

Clearly, adequate heat exchange rate between the iTM and the indoor air is also necessary for a building to achieve small operative temperature variation.

5.4. Wood or Concrete Interior Thermal Mass

Ref. [1] showed that concrete is a better heat storage medium than wood. Here, we will use the RC model to find out how better concrete is than wood as iTM.

According to Ref. [1], for normal-weight concrete, the optimal effective thermal resistance is only 16% of that of wood, and the effective volumetric specific heat is about two times larger than that of wood. Simulation results of wood and concrete as iTM are shown in Table 2. In this table, the iTM thickness (the first row) is doubled each step from left to right except the optimal thermal mass thicknesses (0.162 m for wood and 0.398 m for concrete); the iTM surface area (the first column) is doubled each step from top to bottom; the colored cells are the operative temperature variations. Cells are colored in green when the variation is smaller than 2 °C; in this region, buildings are believed with good thermal comfort. When the variation is bigger than 4 °C, cells are colored in red; such big variations are not accepted for human and extra heating and cooling should be added. Between these two temperatures, cells are colored in yellow; in this range, people can accept but buildings are not considered to be thermally comfortable.

Table 2. Comparison of wood and concrete as interior thermal mass

Wood

area (m^2) \ ΔT_{op} (K) \ thickness (m)	0.025	0.050	0.100	0.162	0.200	0.400
184	9.83	6.79	4.71	4.25	4.29	4.59
368	6.64	3.98	2.65	2.39	2.43	2.64
736	3.84	2.13	1.39	1.26	1.28	1.41
1472	2.03	1.09	0.71	0.65	0.66	0.73
2944	1.04	0.55	0.36	0.33	0.34	0.40

Concrete

material \ ΔT_{op} (K) \ thickness (m)	0.025	0.050	0.100	0.200	0.398	0.400
184	5.53	3.41	2.32	1.88	1.84	1.84
368	3.07	1.78	1.18	0.93	0.92	0.92
736	1.59	0.90	0.58	0.45	0.46	0.46
1472	0.81	0.44	0.28	0.23	0.26	0.26
2944	0.41	0.22	0.15	0.15	0.17	0.17

From Table 2, it is clear: for wood, when the iTM surface area is small, no matter how big the iTM size is, the operative temperature variations are in the red region;

however, when the surface area is large enough, even small size wood iTM can keep the variations in the green region; the operative temperature variations are in the green and yellow regions, even when the concrete iTM size and the heat transfer rate are both small, which means that concrete can control the operative temperature well; concrete is much better than wood as iTM.

6. Conclusion

In this paper, a resistor-capacitor (RC) model of a U.S. prototypical residential house is built in Matlab/Simulink. With the RC model, the roles of exterior thermal mass and interior thermal mass in the house are investigated systematically. It shows that when reasonably changing the concrete or wood thickness, the operative temperature variation can be more easily kept in a smaller range in a concrete-envelope house than in a wood-envelope house with normal amount of iTM. With constant envelope thermal resistance, adequate iTM and sufficient heat exchange rate between iTM and indoor air are both necessary to maintain the operative temperature variation in a small range. Simulation results reveal that concrete is better than wood as both eTM and iTM due to its larger heat capacity from the consideration of heat storage.

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