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Analysis and modeling of building thermal response to investigate the effect of boundary conditions

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Abstract. Thermal load simulation and sensitivity analysis are performed for a building in Tehran by numerical means. A heat conduction equation of the walls, together with appropriate convection and radiation boundary conditions, is simulated numerically to compute temperature distributions in the walls. This research proposes a heat balance method, coupled with a bulk model, to calculate the building thermal load. In the first step, the results of the building thermal load for weather data of Tehran are compared and validated with those of Carrier HAP software, and a good agreement is found between them. The building thermal load depends on the boundary conditions of the building. The influence of the boundary conditions, such as the emissivity of interior and exterior surfaces of the walls and convective coefficients, on the building thermal load, is investigated through the application of a sensitivity analysis. Then, the sensitivity coefficients, which demonstrate the significance and impact of internal and external boundary conditions of walls on the thermal load of the building, are calculated, numerically, using a finite-difference method. The results show that internal radiation is an important component of the building energy balance.

1. Introduction

There are growing concerns about building thermal load and energy consumption and their effects on the global environment. Statistics indicate that buildings are dominant energy consumers in cities. In Iran, 40% of the total energy produced is consumed in buildings [1]. According to the data provided by the National Iranian Gas Company [2], 72% of the consumed energy in the building sector is used for heating. Therefore, predicting the thermal behavior of a building, mainly cooling or heating load behavior, is necessary for optimization of its energy consumption.

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The first simulation models of building thermal load were produced in the 1960s [3]. Today, models for the thermal analysis of a building have a wide variety, ranging from very simple models, such as manual HVAC calculation, to full physical models, such as Computational Fluid Dynamics (CFD). The most exact method seems to be CFD. However, due to high computational time and cost, these techniques are not always applicable [4-6]. In this case, simple models appear more attractive. Among various models, the bulk model is not as complex as CFD, but is somehow accurate. During modeling, thermal exchanges among the elements occur as a result of convection and radiation exchanges at surface boundaries. Predominantly, parameters, such as the emissivity of interior and exterior surfaces of walls and convection coefficients, have an influence on load calculation and energy consumption. They should, therefore, be given specific attention. Sensitivity analysis is a powerful tool to identify the contribution of each parameter to the thermal response of buildings.

Sensitivity analysis has recently received considerable attention, due to its wide engineering applications, such as parameter estimation [7-10], optimization, optimal experimental design and uncertainty or error analysis [11,12]. Gu et al. [13] used sensitivity analysis for analyzing steady and unsteady heat transfer. Duran [14] devoted sensitivity analysis to testing the sensitivity of economical systems, and Kapadia and Anderson [15] studied the numerical sensitivity analysis of fuel cells. Sensitivity analysis of transient three-dimensional heat conduction in a plate during the process of welding was performed by Ivanovic and Sedmak [16], and Salva and Tarzia [17] applied a numerical sensitivity analysis for the simultaneous determination of unknown thermal coefficients through a phase-change process. Sensitivity analysis of a predicted night cooling performance on internal convective heat transfer modeling in TRNSYS was done by Goethals et al. [18], and Lomas and Eppel [19] analyzed the effect of thermophysical properties of walls on the energy consumption of buildings. They applied three sensitivity analysis techniques to building thermal simulation programs: differential sensitivity analysis, Monte Carlo analysis and stochastic sensitivity analysis. Analysis of the building energy balance to investigate the effect of thermal insulation under summer conditions was done by Ballarini and Corrado [20]. They simulated the thermal analysis of the building by means of a numerical simulation tool (EnergyPlus). Sensitivity analysis of the thermal energy flux through a sandwich panel, by varying surface emissivity, was done by Joudi et al. [21]. They introduced a model for calculating the effect of both interior and exterior optical properties of a horizontal roof panel in terms of net energy flux. Athienitis [22] examined the impact of a parameter convection coefficient on the thermal response of buildings using the network theory. Buchberg [23] examined the sensitivity of wall temperature distribution to the external convection coefficient by solving the transient conduction equation of the walls, regardless of radiation between the walls. Zhai and Chen [24] performed a sensitivity analysis of building and environmental characteristics with coupled simulation, building energy simulation and CFD programs, to evaluate the accurate and efficient thermal performance of the building.

In the above work, researchers used simulation programs for determining the building thermal load. However, the goal of this paper is to study the numerical sensitivity of thermal loads and heat transfer, with respect to the boundary conditions of the building. The ultimate aim has been to assess the significance and influence of input design parameters, such as the emissivity of interior and exterior surfaces of walls and the convection coefficients, on the building thermal load. In addition, the modeling and calculations of thermal load are examined, hour-by-hour. For solving direct problems, i.e. energy conservation and heat equations in the building and walls, radiation between internal surfaces of the walls is considered.

2. Building heat conduction

A building includes several heat and mass transfer mechanisms. Transient heat conduction, surface convection, and internal and external radiation are some of the factors that should be considered in building thermal load simulation. One of the most important forms of heat transfer in building simulation is heat conduction through walls, roofs and floors. The transient heat conduction equation of walls is [25]:

$$k\frac{\partial^2 T(x,t)}{\partial x^2}=\rho c_p\frac{\partial T(x,t)}{\partial t}, \qquad 0\langle x\langle l, \tag{1}$$

where $T(x,t)$ is wall temperature, k is thermal conductivity, ρ is density and c_p is specific heat.

The boundary condition of walls on both sides is a conjunction of convection and radiation. The convection boundary condition is due to convective heat transfer with the atmosphere. The radiation boundary condition in the internal and external surfaces is due to the radiative heat transfer mechanism. The boundary conditions of walls are:

$$k\frac{\partial T(0,t)}{\partial x}=h_i[T_{\text{in}}-T(0,t)]+\varepsilon_{\text{int}}q''_s,$$

$$k\frac{\partial T(l,t)}{\partial x}=h_o[T_{\text{out}}-T(l,t)]+\varepsilon_{\text{out}}q''_{\text{sol}}, \tag{2}$$

where $x=l$ is thickness of walls, T_{in} and T_{out} are inside and outside air temperatures, respectively; h_i and h_o are internal and external convective coefficients, respectively; ε_{int} and ε_{out} are emissivity of interior and exterior surfaces, respectively, and q^*_s and q^*_{sol} are heat fluxes in the internal and external surfaces, respectively.

Heat flux in the internal surface is the consequence of thermal radiation between the walls, whereas the surfaces of all walls are opaque and gray. Also, the radiation is uniform in all directions. Radiation exchange between the walls will be the solution of the following equation [26]:

$$\begin{bmatrix} 1-\rho_1F_{1-1} & -\rho_1F_{1-2} & \cdots & -\rho_1F_{1-n}\\ -\rho_2F_{2-1} & 1-\rho_2F_{2-2} & \cdots & -\rho_2F_{2-n}\\ \cdots & \cdots & \cdots & \cdots\\ -\rho_nF_{n-1} & -\rho_nF_{n-2} & \cdots & 1-\rho_nF_{n-n}\end{bmatrix}\begin{bmatrix}J_1\\J_2\\\cdots\\J_n\end{bmatrix}$$

$$= \begin{bmatrix} E_1 \\ E_2 \\ \dots \\ E_n \end{bmatrix}, \tag{3}$$

$$E = \varepsilon_{\text{int}} \sigma T^4, \tag{4}$$

where E is emissive power, σ is Stefan-Boltzmann constant, J is radiosity, ρ is reflectivity and F_{ij}s are shape coefficients between the walls, i and j. After solving Eq. (3), the net energy output from the surface, i, is obtained as:

$$q_i'' = J_i - G_i, \tag{5}$$

where G is irradiation (total received radiation from all objects around).

Heat flux in the external surface (q_{sol}^*) is due to solar radiation, which is given by [27]:

$$q_{\text{sol}}'' = I_b \cos(\theta) \frac{A_{\text{SL}}}{A} + I_{\text{dif}} F_{\text{DS}} + I_G F_{\text{SG}}, \tag{6}$$

where:

$$\begin{aligned} \cos(\theta) = {} & \sin(\delta)\sin(\phi)\cos(\beta) \\ & - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) \\ & + \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) \\ & + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\omega) \\ & + \cos(\delta)\sin(\beta)\sin(\omega)\sin(\gamma), \end{aligned} \tag{7}$$

$$I_G = [I_b \cos(\theta_Z) + I_{\text{dif}}].R_{gr}, \tag{8}$$

$$\cos(\theta_z) = \cos(\delta)\cos(\phi)\cos(\omega) + \sin(\phi)\sin(\delta). \tag{9}$$

Also, I_b and I_{dif} are beam (direct) solar radiation and diffuse solar radiation, respectively (data is provided from the Iran Meteorological Organization [28]), θ is angle of incidence, I_G is beam (direct) radiation of the ground, A_{SL} is the sunlit area of the surfaces, A is the surface area, F_{DS} is the view factor of the walls surface to the sky, F_{SG} is the view factor of the walls surface to the ground, δ is declination (the angular position of the sun at solar noon), ϕ is latitude, β is the slope, γ is the surface azimuth angle, ω is the hour angle, θ_z is the zenith angle and R_{gr} is the reflectivity of the ground. For more information, see [27].

For simulation, first, walls and room characteristics and weather information are defined. Eqs. (3) to (9) must be solved for obtaining radiation boundary conditions. Then, Eq. (1), with boundary conditions (Eq. (2)), can be solved numerically. We used a conventional finite volume approach to solve it. For this problem, the discretized equation is similar to a second order finite difference method. After solving equations, the wall temperature distributions and heat flux into the room are obtained.

3. Building thermal equilibrium

After thermal modeling of the walls and obtaining of the heat flux, room thermal equilibrium must be written. Inside air temperature varies due to heat exchange with the walls and with the inside equipment via convection and also due to the generated heat. Absorbed radiation or emission is negligible. Therefore, temperature distribution in the building using a bulk model is as follows [26]:

$$\begin{aligned} m_{\text{air}} c_{p,\text{air}} \frac{dT_{\text{in}}}{dt} = {} & \sum_i h_i A_i \left(T_{s,i} - T_{\text{in}}\right) \\ & + h_{\text{fur}} A_{\text{fur}} \left(T_{\text{fur}} - T_{\text{in}}\right) + Q_{\text{gen}}, \end{aligned} \tag{10}$$

where $T_{s,i}$ and T_{fur} are the temperature of surface i (walls, roof ...) and the temperature of furniture in the room, respectively; m_{air}, $c_{p,\text{air}}$ and T_{in} are mass, specific heat capacity and room air temperature, respectively; h_i and h_{fur} are the heat transfer coefficients of the surface and furniture in the room, respectively, and Q_{gen} is the heat generation. The furniture may have a temperature gradient inside; however, due to the complexity of the model, the gradient is neglected in the present work. Heat balance for the furniture is as follows:

$$m_{\text{fur}} c_{p,\text{fur}} \frac{dT_{\text{fur}}}{dt} = -h_{\text{fur}} A_{\text{fur}} \left(T_{\text{fur}} - T_{\text{in}}\right) + q_{\text{Rad, in}}, \tag{11}$$

where T_{fur} is the average temperature of the furniture and $q_{\text{Rad, in}}$ is the net radiation of heat into the furniture.

After thermal modeling of the walls and obtaining of heat flux, by solving conservation equations (Eqs. (10) and (11)), the thermal load is calculated employing an iterative algorithm.

4. Sensitivity study of thermal simulation

This study conducts a sensitivity analysis of the building thermal response to the boundary conditions. Sensitivity analysis evaluates the significance and impact of input design parameters and identifies important characteristics of the input variables on the corresponding temperature and thermal load. For thermal problems, sensitivity analysis is the observation of the partial derivative of the state variable, such as temperature and thermal load (for this work), with respect to model parameters. This partial derivative is called the sensitivity coefficient, J, with respect to parameter P [29]:

$$J = \frac{\partial q}{\partial P}. \tag{12}$$

Because a comparison of magnitudes for different coefficients is often of interest, a modified (scaled) sensitivity coefficient is used [30]:

$$J_{P_i} = P_i \left[\frac{\partial q}{\partial P_i}\right]_{P_j, j\neq i}, \tag{13}$$

where P_i is a particular solution parameter (e.g. emissivity of interior and exterior surfaces of the walls (ε_{int} and ε_{out}), or the convection coefficients (h_i and h_o)) and P_j specifies other parameters that are kept constant.

There are several approaches for computation of sensitivity coefficients. Three main approaches include [29]:

1. Direct analytic solution: If an analytic solution is available for a direct problem, the sensitivity coefficient, with respect to parameter P_i, is determined by differentiating the solution with respect to P_i.
2. The boundary value problem approach: A boundary value problem can be developed for determining the sensitivity coefficient by differentiating the original direct problems and their boundary and initial conditions, with respect to parameter P_i, and finally, solving the obtained equations.
3. Discretization of Eq. (13): By this method, the first derivative appearing in the definition of the sensitivity coefficient, Eq. (11), can be computed, for example, by finite differences.

Sensitivity analysis using the direct method is suitable for modeling with few parameters and simple geometry. For analyzing complex problems with irregular geometry or multiple materials, it is better to use numerical methods, including a boundary value problem approach and finite-difference approximation. In this paper, due to the existence of radiation between the walls, each wall temperature distribution, including the thermal load imposed on the building, are completely dependent on the properties of other walls. Therefore, the third method (finite difference approximation) is used here. Thermal load, temperature distribution and sensitivity coefficients of all walls and buildings can be obtained by changing the parameters of each wall. In this method, the direct problem must be solved twice to obtain the sensitivity coefficient in the direct model. Thermal load (q) is calculated, once with the base parameter value, P, and then with the perturbed parameter value, $P+\Delta P$. Therefore, sensitivity coefficients are calculated by a finite-difference approximate derivative as below:

$$J = \frac{\partial q}{\partial P} = \frac{q(P+\Delta P) - q(P)}{\Delta P}. \tag{14}$$

Based on the sensitivity analysis, a set of sensitivity coefficients of boundary conditions can be obtained. A small sensitivity coefficient is beneficial in instances where the parameters are not well quantified, such as a material with emissivity that is not characterized. Then, the parameter has no influence on thermal response.

5. Model descriptions

To determine influential parameters on building thermal response, a sample building is considered in Tehran. The selected building is a rectangular zone with dimensions $L \times W \times H = 4$ m $\times$ 5 m $\times$ 3 m, with four exterior walls and no windows. Room air temperature is assumed 21°C. Walls are composed of gypsum board, LW concrete block and face brick. The roof is made from steel deck, board insulation and built-up roofing. For the sensitivity analysis, uniform and equal properties are assumed for all material layers of the walls and roof. The materials used for the walls and roof are shown in Table 1. Model input data, i.e. climatic data of Tehran, include temperature and solar radiation fluxes. Temperature is extracted from the Iran Meteorological Organization and the solar radiation fluxes are obtained from Eqs. (5) to (8). A simulation of the building is calculated for

Table 1. Materials used for a room.

Item	Layer	Thickness (mm)	Specific heat ($\mathrm{kJkg^{-1}K^{-1}}$)	Density ($\mathrm{kgm^{-3}}$)	Conductivity ($\mathrm{Wm^{-1}K^{-1}}$)	Interior emissivity [-]	Exterior emissivity [-]
Walls	3	71.6	0.895	1271.47	0.4987	0.9	0.9
		71.6	0.895	1271.47	0.4987	0.9	0.9
		71.6	0.895	1271.47	0.4987	0.9	0.9
Roof	3	45	1.249	1071.24	0.10087	0.9	0.9
		45	1.249	1071.24	0.10087	0.9	0.9
		45	1.249	1071.24	0.10087	0.9	0.9

two 72-hour periods, one in July and the other in January.

6. Results and discussion

This section presents the results of thermal simulation and the effect of boundary conditions on the building thermal load, namely, sensitivity analysis.

6.1. Thermal simulation results

Based on the introduced model in the previous section, a computer program is developed for calculating surface temperatures and the heating and cooling loads imposed on the room. The above dynamic model is first validated by comparing the present results with those of Carrier HAP software in two different one-day periods; one in July (summer) and the other in January (winter). It is worth noting that for this validation, temperature data and solar radiation fluxes of Tehran are extracted from Carrier HAP software. Figure 1 shows the results for cooling and heating loads during one day in July (Figure 1(a)) and in January (Figure 1(b)). The comparisons show that cooling and heating loads are in close agreement with Carrier HAP results. There is a 5% difference in daily cooling load and a 12% difference in daily heating load between the present results and Carrier HAP results. Thus, the present computer code for the cooling and heating loads is reliable and valid.

6.2. Sensitivity analysis of boundary conditions

After code validation, the same numerical model is used for sensitivity analysis in order to explore the effect of input parameters on the building thermal load. For sensitivity analysis, some of the influential parameters of boundary conditions on the building cooling and heating loads are considered and shown in Table 2. The list includes emissivity of interior and exterior surfaces of the walls and convective coefficients. The modified sensitivity of cooling and heating loads, with respect to the above parameters of the walls and roof, for a 72-hour period in the months of July and January, is obtained.

The modified sensitivity of the cooling load is shown in Figure 2 for the north wall, Figure 3 for the east wall, Figure 4 for the south wall, Figure 5 for the west wall and Figure 6 for the roof.

Figure 2 shows that the emissivity (both interior and exterior) of the north wall plays a significant role in the cooling load. For the east wall (Figure 3), sometimes, external boundary conditions are more effective than internal boundary conditions. As shown in Figure 4, the sensitivity of the cooling load to

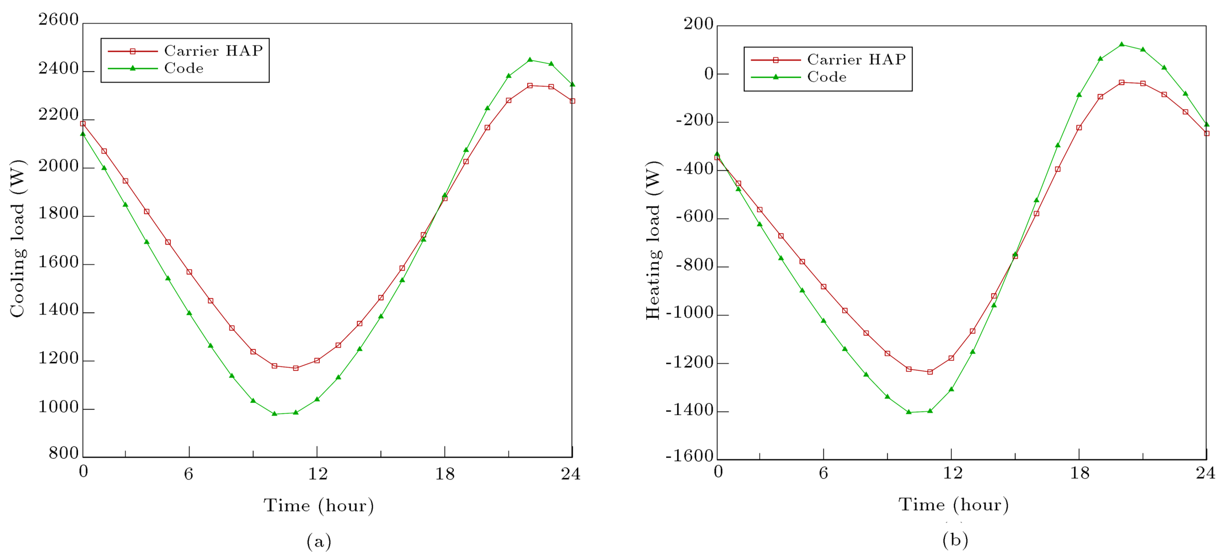

Figure 1. Comparison of the results of carrier HAP software and the present work for hourly loads in a) July, and b) January.

Table 2. Overview of parameters for sensitivity analysis.

Item	Internal convection coefficient ($Wm^{-2}K^{-1}$)	External convection coefficient ($Wm^{-2}K^{-1}$)	Interior emissivity [-]	Exterior emissivity [-]
Walls	8.29	17.05	0.9	0.9
Roof	8.29	17.05	0.9	0.9

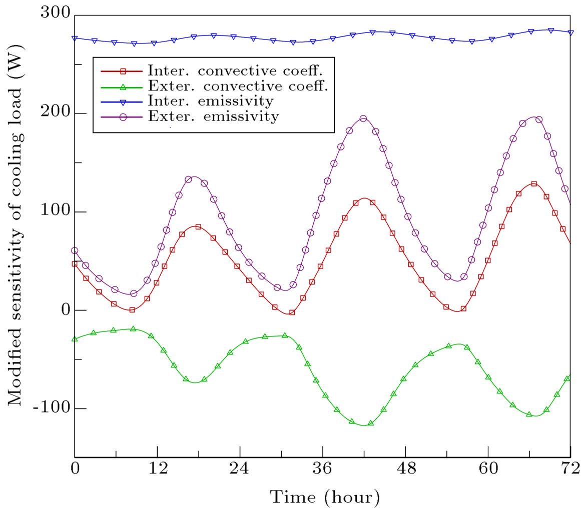

Figure 2. Modified sensitivity of cooling load with respect to boundary conditions of the north wall.

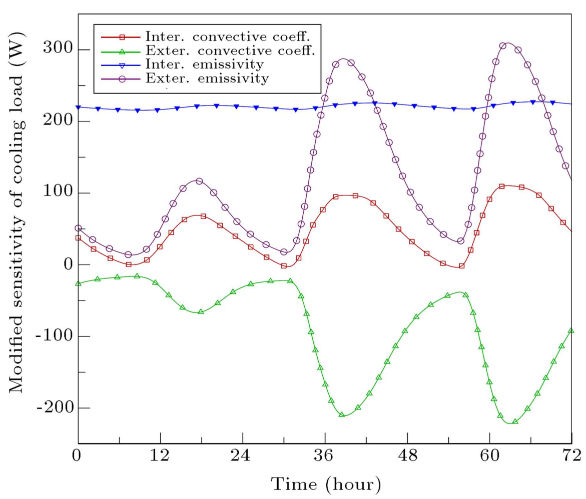

Figure 3. Modified sensitivity of cooling load with respect to boundary conditions of the east wall.

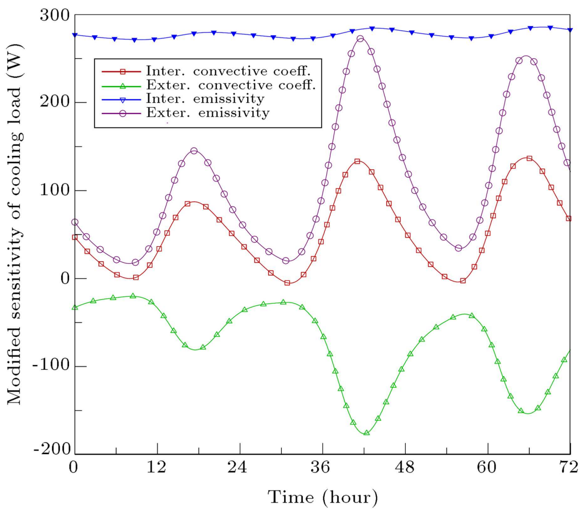

Figure 4. Modified sensitivity of cooling load with respect to boundary conditions of the south wall.

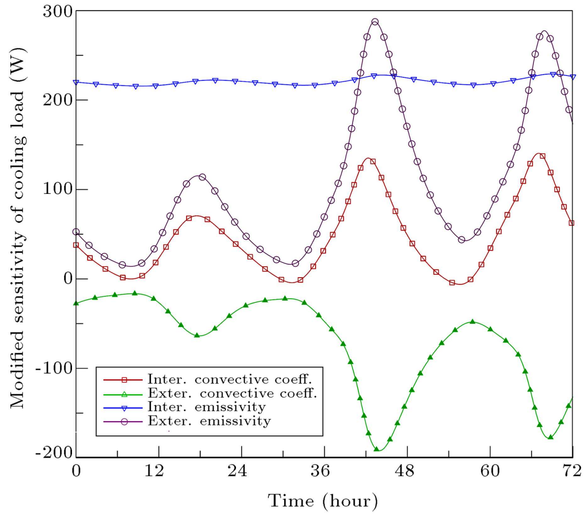

Figure 5. Modified sensitivity of cooling load with respect to boundary conditions of the west wall.

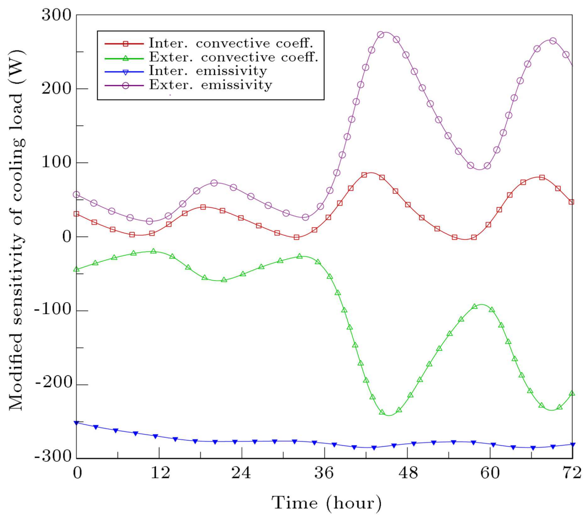

Figure 6. Modified sensitivity of cooling load with respect to boundary conditions of roof.

the emissivity of the interior and exterior surfaces of the south wall is maximum. Figure 5 shows that, similar to the east wall, sometimes, the emissivity of the exterior surface is more effective than the emissivity of the interior surface on the building cooling load. Figure 6 represents the maximum values of sensitivity, with respect to the emissivity of the roof.

The modified sensitivity of the heating load is shown in Figure 7 for the north wall, Figure 8 for the east wall, Figure 9 for the south wall, Figure 10 for the west wall and Figure 11 for the roof. As can be seen in Figure 7, the emissivity of the interior surface and the external convection coefficient has the greatest amount, respectively. For the east wall (Figure 8), sometimes, external boundary conditions are more effective than internal boundary conditions, and Figure 9 illustrates

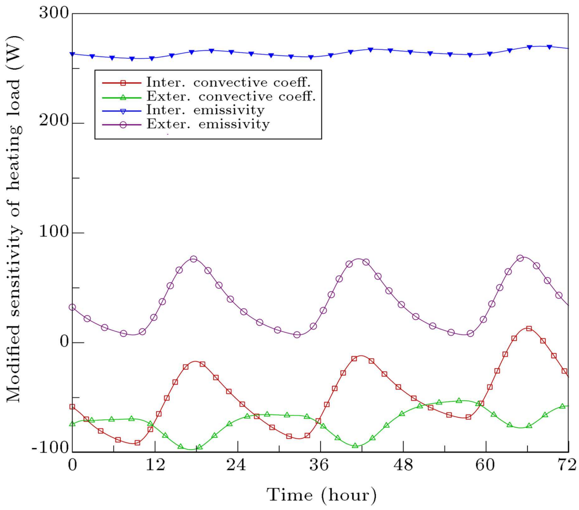

Figure 7. Modified sensitivity of heating load with respect to boundary conditions of north wall.

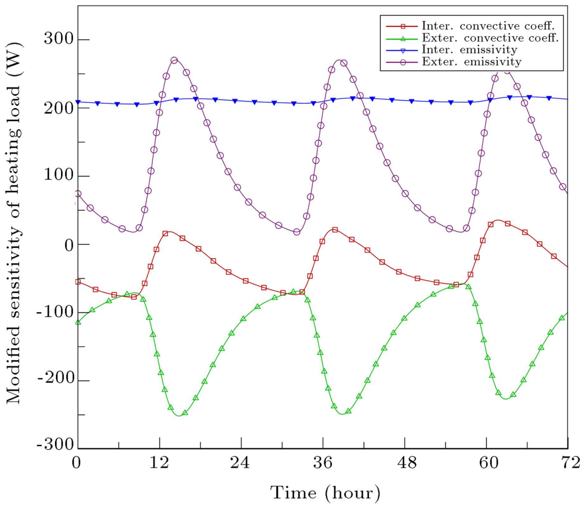

Figure 8. Modified sensitivity of heating load with respect to boundary conditions of the east wall.

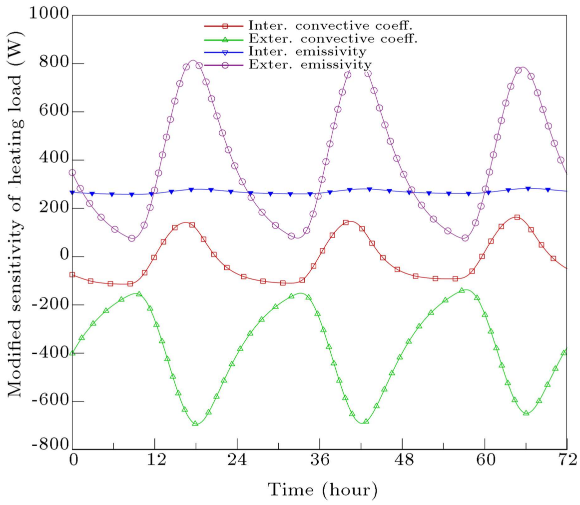

Figure 9. Modified sensitivity of heating load with respect to boundary conditions of south wall.

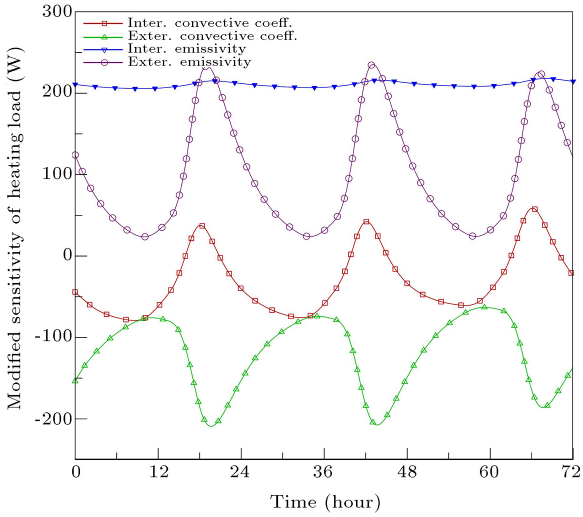

Figure 10. Modified sensitivity of heating load with respect to boundary conditions of west wall.

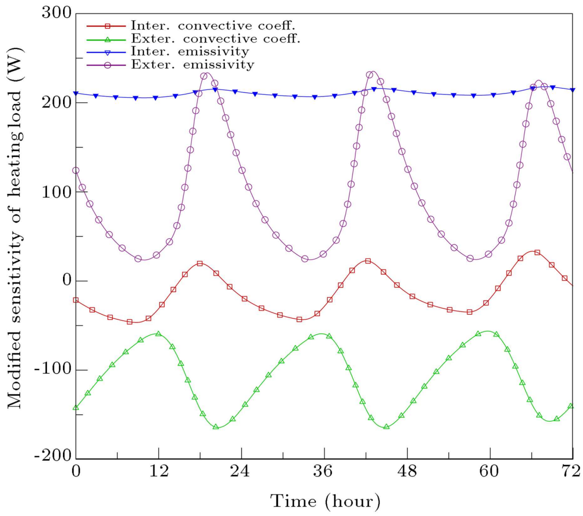

Figure 11. Modified sensitivity of heating load with respect to boundary conditions of roof.

this fact. Figure 10 shows that an external convection condition is more effective than the emissivity of the exterior surface on the building heating load. Figure 11 represents the maximum value of sensitivity, with respect to the emissivity of the interior surface of the roof in January.

It should be noted that the effect of the external convection coefficient on the building cooling and heating loads is more than that of the internal convection coefficient.

From the presented results, it can be found that boundary conditions of the roof and east wall, due to direct solar radiation in summer, have the most effect on the building cooling load, respectively. Also, the building heating load is more affected by the boundary conditions of the south wall, which is exposed to maximum solar radiation in winter.

7. Conclusions

A dynamic computer simulation is carried out in the climate of Tehran, Iran. The thermal load of a room using conventional finite-volume is determined. Secondly, a sensitivity analysis of the building thermal response, with respect to boundary conditions (emissivity of interior and exterior surfaces of the walls and convective coefficients), is obtained. As observed in the sensitivity analysis, the emissivity of interior surfaces and the external convection coefficient have the greatest effect on building cooling and heating loads, respectively.

Analysis results show that the roof is the most important structural element of the building in summer. Also, the present study shows that the building heating load is more sensitive to the boundary conditions of the south wall. Therefore, for reducing the building cooling and heating loads and energy consumption, due attention must be paid when designing these walls and roofs.

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