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# Comparison of heat gain values obtained for building structures with real and constant properties

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**Abstract**
The magnitude of energy consumption due to the heating and cooling of buildings has led to the demand for increasing the thermal performance of building structures. Many investigations are presented in literature arguing to find the effect of each thermophysical property on the thermal characteristics of building components, while the properties have been assumed as independent of each other. In this context, this paper focuses on the effect of each property on heat gain value utilizing relationships between the measurement values of the thermophysical properties of building structures. In the previous study, 102 new wall samples were produced, their thermophysical properties were tested and expressions among these properties are obtained. In this study, the heat gain values through the structures are computed using the solution of the transient heat transfer problem by using both the obtained expressions between the thermophysical properties and assumptions proposed from the literature. Results obtained for varying and constant thermophysical properties have been compared with those values presented in the literature. The results show that the assumptions are not realistic in a significant number of cases. Moreover, if one of the thermophysical properties of a material is known, heat gain values can be calculated easily for the selected wall or roof types.

**Keywords:** Building wall, roof, thermophysical properties, heat gain, CFFT

# Gerçek ve sabit özellikli bina yapıları için elde edilen ısı kazanç değerlerinin karşılaştırılması

**Öz**
Binaların ısınması ve soğutulmasından kaynaklanan enerji tüketiminin büyüklüğü, bina yapılarının ısıl performansının artırılması talebine yol açmıştır. Literatürde sunulan birçok araştırmada, her termofiziksel özelliğin yapı bileşenlerinin ısıl özellikleri üzerindeki etkisini bulmayı tartışılırken, bu çalışmalarda özelliklerin birbirlerinden bağımsız olduğu varsayılmıştır. Bu bağlamda, bu çalışmada, her bir özelliğin bina yapılarının termofiziksel özelliklerinin ölçüm değerleri arasındaki ilişkilerini kullanarak, ısı kazanç değerleri üzerindeki etkilere odaklanılmıştır. Önceki çalışmada 102 yeni duvar numunesi üretilmiş, termofiziksel özellikleri test edilmiş ve bu özellikler arasında ifadeler elde edilmiştir. Bu çalışmada, yapılardaki ısı kazanç değerleri geçici ısı transferi probleminin çözümü kullanılarak hem termofiziksel özelliklerden hem de literatürde ileri sürülen varsayımlardan elde edilen ifadeler kullanılarak hesaplanmıştır. Değişen ve sabit termofiziksel özellikler için elde edilen sonuçlar literatürde sunulan değerlerle karşılaştırılmıştır. Sonuçlar, varsayımların çok sayıdaki durumda gerçekçi olmadığını göstermektedir. Ayrıca, bir malzemenin termofiziksel özelliklerinden biri biliniyorsa, seçilen duvar veya çatı tipleri için ısı kazanç değerleri kolayca hesaplanabilmektedir.

**Anahtar kelimeler:** Bina duvarı, çatı, termofiziksel özellikler, ısı kazancı, CFFT

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## 1. Introduction

A great amount of energy consumption in the world is expended through building heating and cooling systems. Energy requirements of a building for the winter and summer seasons consist of heat losses or gains through walls, ceilings, windows, infiltration, and types of equipment used. Building walls and roofs are responsible for a major portion of heat loss or gains due to their large surface area [1]. Therefore, it is very important to decrease the heat loss or gains of these structures and to improve the thermal comfort of humans lived in the building. The magnitude of heat loss and gains through building structures depends on environmental conditions (ambient air temperature, solar heat flux, ventilation, etc.), design parameters (orientation, solar absorptivity, emissivity, etc.) and thermophysical properties (thermal conductivity, specific heat, density, thickness, etc.) [2]. It is not possible to change environmental conditions. Orientations of buildings may change heat loss or gain an indefinite amount. However, improvements in thermophysical properties of the building structure are possible to decrease heat losses or gains.

Yumrutas et al. [3-5] developed an analytical method for multilayer walls based on the periodic solution of the periodic heat transfer problem to calculate the TETD values of the building structures. The calculation results showed that high solar radiation incident and ambient air temperature give higher TETD and heat gain values. Ülgen [6] investigated the thermal behavior of opaque wall materials under the change of solar energy and the interaction between the thermophysical properties of wall materials and the solar energy falling on the outer surface of the wall. Furthermore, the thermal behavior of opaque wall materials under the influence of solar energy was investigated by Vijayalakshmi et al. [7]. They analyzed the effects of the thermophysical properties of different wall types. Sanea et al. investigated the effect of the location and different amounts of thermal mass on the dynamic heat transfer properties of insulated building walls under steady periodic conditions using Riyadh's climatic data [8]. It is found that maximum savings are about 17% and 35% in yearly cooling and heating loads, respectively. Besides, various studies have been conducted on the effect of the thickness and location of the insulation layer of a wall on the dynamic thermal properties of building components. They have shown that the thickness and insulation position have a significant effect on heat gain or loss [9-12].

Studies cited above indicate that the dynamic thermal characteristics of the building components depend on many factors, such as the outdoor climate condition, building configuration, etc. in a specific region. Many investigations declared that these characteristics strongly depend on the thermophysical properties of the building's layer materials [13–20]. For building heat transfer, important thermophysical properties of building's layer material are thermal conductivity, specific heat, density, thickness, and thermal diffusivity. By the way, the thermophysical properties of a building material are significantly influenced by microstructure, mineralogical composition, proportion, additional materials, moisture content and porosity [21]. Many studies have shown that there is a relationship among the thermal conductivity, specific heat, and thermal diffusivity of building materials [22-25]. Although many studies have been conducted to investigate the effect of the thermophysical properties of opaque components on their dynamic thermal characteristics, the current practices ignore the relationship between these properties. The experimental study [22] indicates that thermophysical properties depend on each other. Since there has not been conducted any research in literature, there is still a lack of information.

In this study, the effect of each thermophysical property on the heat gain through the wall or roof has been investigated by taking into account the relationships between these properties. In a previous study [22], 102 new wall samples were produced, and their thermophysical properties were tested according to ASTM and EN standards. Then, multivariate regression analyses were performed and expressions among these properties were obtained using the measurement data. Analytical periodic solution obtained by applying Complex Finite Fourier Transform (CFFT) method has been used for calculation of space heat gain through the walls or roofs by using the expressions obtained from an experimental study. Finally, the heat gain values are calculated using both the obtained expressions and the assumptions proposed from the literature, and comparisons have been discussed. Both experimental and theoretical procedures, and also their results are presented in the following sections.

# 2. Formulation of the heat transfer model

## 2.1. A periodic solution of the problem

Heat transfer from a building component to the room is a function of the interior wall surface and solar-air temperature. The heat flux passing through the room can be calculated using the inner surface temperature, the combined heat transfer coefficient on the surface and the room temperature. The heat transfer problem and its solution procedure for finding the temperatures will be given in this section.

The following assumptions were made for the solution of the problem:

a) no internal heat generation in any layer of walls,
b) each layer has a homogeneous structure with fixed thermo-physical properties,
c) the resistance of the layer interface is neglected for good contact of the layers,
d) the combined convection (both radiation and convection) coefficients are constant.

The transient heat transfer from the building structures to a room is presented as the following partial differential equations under given boundary conditions:

$$\frac{\partial^2 T_n}{\partial x^2_n} = \frac{1}{a_n}\frac{\partial T_n}{\partial t} \qquad 1 \le n \le N \tag{1}$$

$$h_i(T_r - T_1) = -\lambda_1 \frac{\partial T_1}{\partial x_1} \qquad x_1 = 0 \tag{2}$$

$$-\lambda_{n-1}\frac{\partial T_{n-1}}{\partial x_{n-1}}(x_{n-1} = L_{n-1}) = -\lambda_n \frac{\partial T_n}{\partial x_n}(x_n = 0) \qquad 2 \le n \le N \tag{3}$$

$$T(x_{n-1} = L_{n-1}) = T(x_n = 0) \qquad 2 \le n \le N \tag{4}$$

$$-\lambda_N \frac{\partial T_N}{\partial x_N} = h_o\left[T_N - T_e(t)\right] \qquad x_N = L_N \tag{5}$$

$$T_e(t) = T_a(t) + \frac{\alpha_s I_T(t)}{h_o} - \frac{\varepsilon\,\Delta R}{h_o} \qquad x_N = L_N \tag{6}$$

where $n$ is layer number, $h_i$ and $h_o$ are the combined convection heat transfer coefficients at the inner and outer surfaces, $T_e(t)$ is the hourly sol-air temperature, $T_a(t)$ is ambient air temperature and $\alpha_s$ is solar absorptivity coefficient for the outer surface of the building wall. $\varepsilon\,\Delta R / h_o$ in Eq. (6) is defined as the correction factor given in ASHRAE [26], which is specified to be 4°C and 0°C for horizontal and vertical surfaces, respectively. $I_T(t)$ is the hourly solar heat flux on a tilted surface, which can be expressed as the sum of the beam, diffuse and reflected radiation. The solar radiation incident on tilted surfaces is calculated using the expressions and procedure in Ref. [27] by taking ground reflectance of 0.2.

The heat transfer problem consisting of Eqs. (1)–(6) is put into a dimensionless form using dimensionless parameters, and solved to obtain a periodic solution by an application of the dimensionless formulation by CFFT. The solution of the f dimensionless formulation was detailed in Yumrutas et al. [3], and the solution equation giving temperature distribution through a building wall is expressed as:

$$T_n(z_n, \tau) = \sum_{j=-M}^{M} T_{nj}(z_n)\, e^{i\omega_j \tau}, \qquad \omega_j = 2\pi j \tag{7}$$

where $z_n$, $\tau$, $\omega_j$, and $T_{nj}$ are dimensionless parameters. $M$ is the large number and generally taken as 60. To find inner wall surface temperature, n and $z_n$ should be equal to zero:

$$T_1(0, \tau) = \sum_{j=-M}^{M} T_{1j}(0)\, e^{i w_j \tau} \qquad z_n = 0 \tag{8}$$

Also, $q$ is the heat gain (W/m$^2$) through the indoor space of a building from exterior walls. It can be calculated using the inner wall surface, $T_1(0,\tau)$ and room temperature, $T_r$, and combined convection heat transfer coefficient at the inner surface, $h_c$.

$$q = h_c\left[T_1(0,\tau) - T_r\right] \qquad z_n=0 \tag{9}$$

### 2.2. Validation of the heat transfer problem

To show the reliability of the present study, we compare the heat gain values calculated using the solution of heat transfer problem obtained by the CFFT technique with the model given in Ref. [16]. Figure 1 is illustrated for comparing heat gain values of Jin et al. [16] with those obtained from the CFTT for the selected wall, respectively. In both models, the daily variation of solar-air temperature is assumed to be sinusoidal, room temperature, $T_r$, the combined heat transfer coefficients at inner and outer surfaces, $h_i$ and $h_o$, are considered as 26 °C, 8.7 and 18.6 W/m$^2$ °C, respectively.

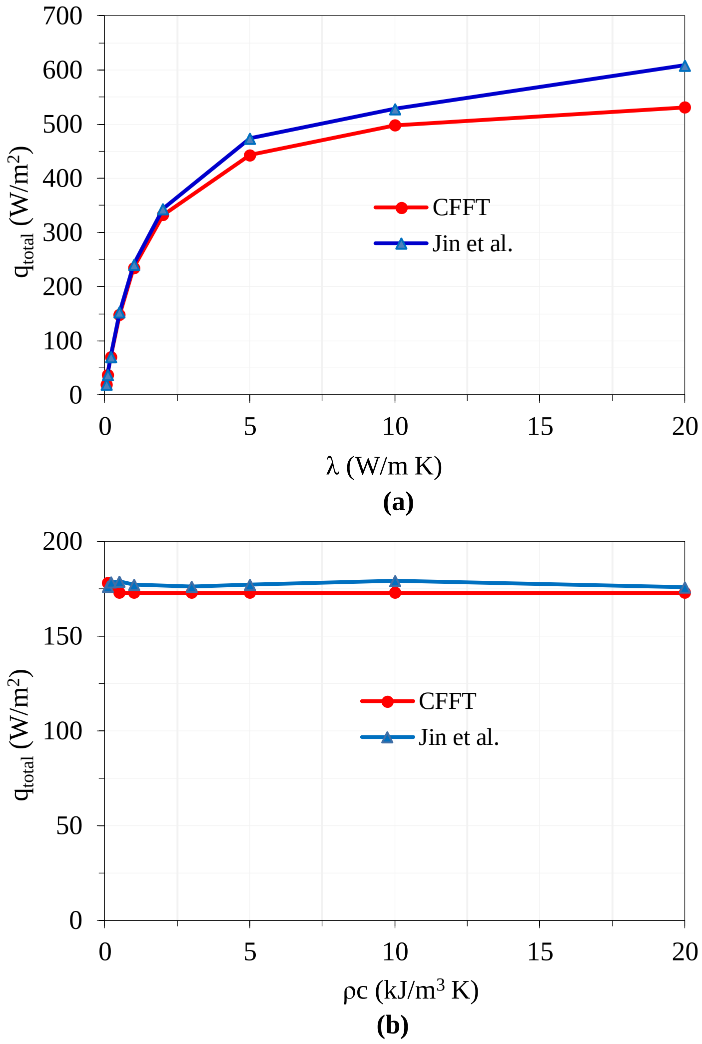


**Figure 1.** A comparison between the method of Jin et al. [16] and CFTT in the calculation of heat flux due to the variation of thermophysical properties: (a) with constant heat capacity (b) with constant thermal conductivity

In Figure 1a, the thermal capacity of the wall is held constant as 1.512 MJ/m$^3$ K and the thermal conductivity of the wall is varied between 0.05 W/m K and 20 W/m K. Meanwhile, in Figure 1b, the thermal conductivity of the wall is held constant as 0.62 W/m K, the thermal capacity of the wall is varied between 0.1 MJ/m$^3$ K and 20 MJ/m$^3$ K. When the results are compared to each other, it can be observed that the heat gain values calculated by the CFFT method are in good agreement with the results of Jin et al. However, in Jin et al., the estimation of heat flux values based on the assumptions is unreasonable because the relationships between the thermophysical properties of the wall material are taken into account as independent of each other. This conflict is discussed thoroughly in the following sections.

## 3. Analytical Correlations

Thermophysical properties have a profound effect in terms of thermal performance of building structures. In what regards the use of methods in the literature, many studies have been conducted to investigate the influences of the thermophysical properties of building components on their dynamic thermal characteristics. However, the related analyzes presented in the studies have been made based on considering the thermophysical properties of building elements as independent of each other that just allows a rough estimation. To find the effect of each property on heat gain through the wall or roof, an experimental investigation is presented using the thermophysical relations obtained from 102 different building wall or roof materials. In the previous study, several mixtures were produced and their thermophysical tests, which are density, thermal conductivity, specific heat, and thermal diffusivity, were performed according to ASTM and EN standards [22]. To evaluate possible correlations between measurement values of the thermophysical properties of building structures, multivariate regression is performed on the dataset of 102 tested wall samples using the free statistical software found in Microsoft Excel. The test results for the thermophysical properties are presented in Ref. [22]. The range of the samples' property values is large enough to cover the most common elements in building construction that can be used for both structural (beam, column) and non-structural (wall, roof) purposes.

The accuracy of the regression model is calculated by the square of the multiple determination coefficient, $R^2$. The closer $R^2$ to unity, the better the model fits the data. The following expressions regarding thermophysical properties are expressed as a function of the dry density with $R^2$ = 0.95 [22]:

$$\lambda = 0.0676e^{0.0015\rho} \tag{10}$$

The similar variations obtained in reported previous works among lightweight concretes and other building structures [23–25]. Furthermore, the other expressions obtained from the same analysis are presented as a function of the dry density [22]:

$$c = 1427.1e^{-0.0003\rho} \tag{11}$$

$$a = 0.0757e^{0.0012\rho} \tag{12}$$

with $R^2$ = 0.97 and $R^2$ = 0.93, respectively.

The results clearly show a strong relation between the density and the other properties of the wall samples. Correlations obtained present study show that there is a linear relationship among density, thermal conductivity, thermal diffusivity, and effusivity and an inverse relationship exists between density and specific heat. The relationships among the properties are explained and discussed in detail in Ref. [22].

However, an important question remains: "What will the situations be for different building structures and the properties out of these ranges?" In order to give a correct answer to this question, it is required to make a comparison between the relations obtained from test samples and different building structures in terms of thermophysical properties. A comparison between the relations obtained from tested samples and a comprehensive list of building structures [28] are presented in Figure 2 and Figure 3, respectively. It can be concluded that the relations obtained from this study proved to have a similar tendency to those relations reported in the literature and covered all other building structures. However, the expressions should be used with care for the properties out of the tested range.

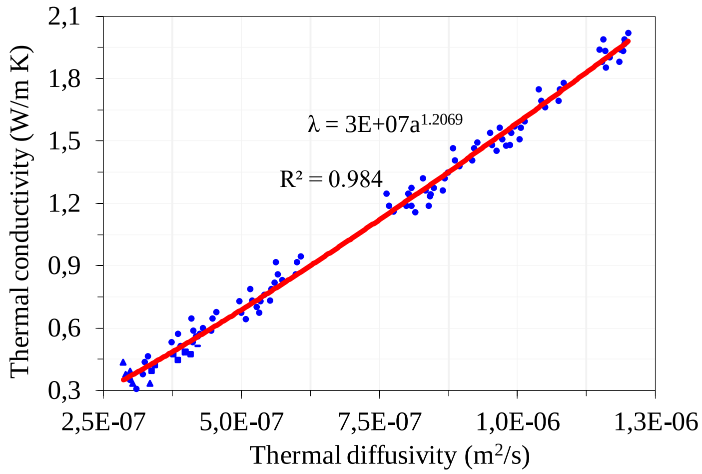


**Figure 2.** Relationship between the thermal diffusivity and the thermal conductivity obtained experimental study.

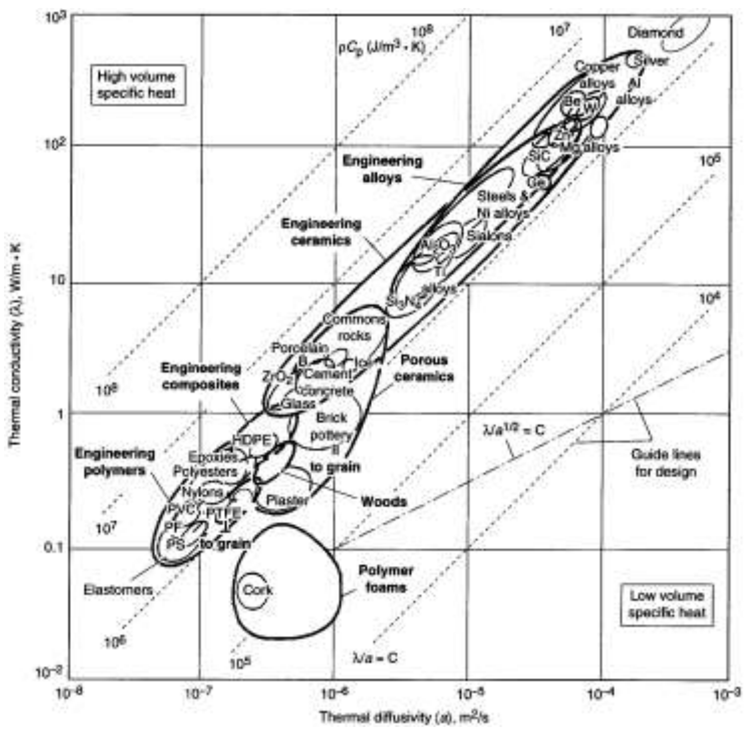

**Figure 3.** A comprehensive list of building materials: Thermal conductivity, $\lambda$, plotted against thermal diffusivity, $a$ for room temperature [28].

## 4. Computational procedure

In order to recognize the nature of the relationships between heat gain and thermophysical properties for building walls or roofs, it is required to examine them within the representative set of structures having different thermal properties. When environmental parameters such as ambient air temperature, solar heat flux, ventilation, etc. and design parameters (orientation, solar absorptivity, emissivity, etc.) are held constant, the heat gain values only depend on thermophysical properties of a building structure. In this context, a computer program in MATLAB was prepared by using climatic data, which are hourly ambient air temperature and solar radiation on a horizontal surface, and thermophysical properties of the produced samples. The program uses the following parameters as input: climatic data, thermophysical properties of the building structures, combined convection heat transfer coefficient for both sides of surfaces, and inside design air (room) temperature. The climatic data was measured by meteorological stations for Gaziantep province (latitude: 37.04 ˚N, longitude: 37.31˚E) on July 21. The room temperature, the combined heat transfer coefficients at the inner and outer surfaces are taken as 24 °C, 8.3 and 17 W/m$^2$ °C, respectively. Solar absorptivity ($\alpha_s$ in Eq. (9)) which depends on the external face color of a building envelope, is generally assumed to be 0.884 (dark-colored surface). The solar radiation incident on a horizontal surface and vertical surface due to south, hourly ambient air and sol–air temperatures are indicated in Figure 4.

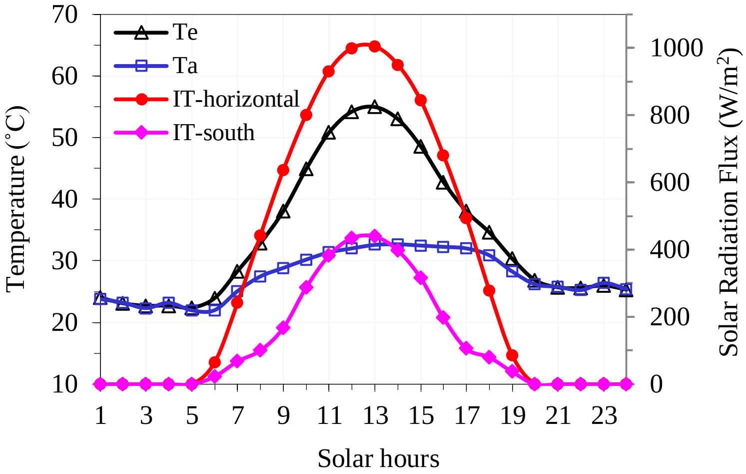


**Figure 4.** The climatic data for Gaziantep province

When the program is first executed, the hourly sol-air temperature in Eq. (6) is computed, and then the inner surface temperature and heat gain through the wall or roof are computed by Eqs. (8) and (9). To establish the relation between each property on heat gain, firstly, the values of heat gain are calculated for each wall or roof assembly with different thermophysical properties by using expressions between (10) and (12) then the curve for calculated data points versus each thermophysical property is plotted and best-fit curve is presented for the plotted data points in the figures.

## 5. Results and Discussion

The heat gain calculations are performed for four different wall types and three different roof types and schematic view of a multilayer wall or flat roof configurations used in this study are represented in Figure 5.

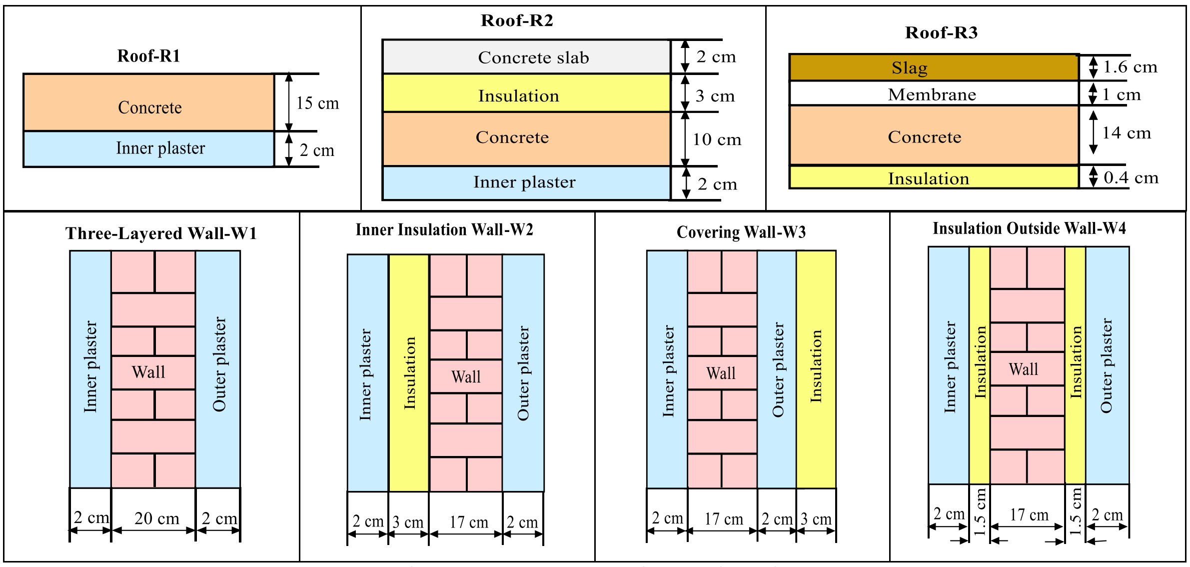


**Figure 5.** Schematic view of a multilayer wall or flat roof configurations used in this study.

Firstly, the peak heat gains are calculated for W1 wall assembly using both the correlations obtained by Eqs. between (10) and (12) and the assumptions proposed from the literature (one property is changed while the others are fixed). The other thermophysical properties of building structures given in the wall and roof assemblies such as plaster, insulation, are presented in Table 1. The expressions obtained from the experimental study are presented in each figure and the comparisons have been made. In the calculations, the thicknesses of the wall and roof assemblies are selected as 24 cm and 17 cm, respectively.

**Table 1.** Thermophysical properties of building materials

| Building materials | Thermal conductivity, $\lambda$ (W/m K) | Density, $\rho$ (kg/m$^3$) | Specific heat, $c$ (J/kg K) | Thermal diffusivity, $\alpha$ (mm$^2$/s) |
|---|---|---|---|---|
| Plaster | 0.700 | 2778 | 840 | 0.30 |
| EPS | 0.038 | 18 | 1500 | 1.40 |
| Membrane | 0.19 | 1121 | 1670 | 0.10 |
| Slag | 1.436 | 881 | 1670 | 0.98 |

The south-facing wall is responsible for most heat gain among the building walls due to the effect of the solar radiation incident. Hence, the calculations are performed for the walls due to south orientations. The effect of the density on the peak heat gains for south-facing structures is shown in Figure 6. In this figure, the peak heat gains through the wall assembly (W1) are calculated with respect to the density variation of real and constant property material where real material denotes the wall materials whose properties are obtained from experimental study and constant property material represents the wall material whose properties are assumed as constant. Figure 6 depicts that while there is a linear relationship between the peak heat gain and the density ($R^2$=0.936) for real wall material, there is an inverse relationship exists between the peak heat gain and the density ($R^2$=0.999) for constant property wall material. The heat gain values increase with the increasing amount of the density for real wall material, while the decrease for constant property wall material. For real wall material, the reduction in the peak heat gains is due to the linear relationship among the density, the thermal conductivity and diffusivity values as presented in Eqs. (10)–(12), respectively. On the contrary, for constant property wall material, the constant thermal conductivity and the specific heat lead to a decrease in the thermal diffusivity with the increase of the density. The results show that 50.17 % increase in the density corresponds to 60.93 % increase in the value of peak heat gain for real wall material with a thickness of 24 cm (W1). Moreover, the test method for the density is relatively simple, rapid, and inexpensive. Therefore, if the density of building material is known, the peak heat gains can be calculated easily for selected walls by using the expression in Figure 6.

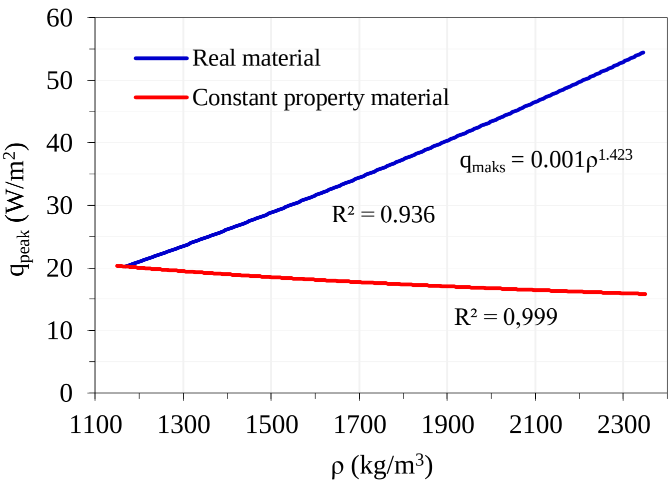


**Figure 6.** Comparison of the effect of the density on the peak heat gains through the walls for real material and constant property material walls due to south direction.

Thermal conductivity variations of elaborated both real and constant property wall materials have a similar tendency to their density variations. It is depicted from Figure 7 that the peak heat gains through the wall assembly (W1) for real and constant property material develop a linear function with $R^2$=0.983 and $R^2$=0.986, respectively. However, the increasing tendencies for those walls are not the same. This is owing to the fact that for real wall material, there is an inverse relationship between specific heat and density. Thereby, there is a direct relationship between the density and thermal conductivity as presented in Eqs. (10) and (11), respectively. On the other hand, an increase in the density value is greater than a decrease in the specific heat value of materials that leads to a reduction in the increasing tendency of the thermal diffusivity values. When the density and specific heat values are fixed (constant heat capacity) for constant property wall material, an increase in the thermal diffusivity only results from increasing the values of thermal conductivity. The result shows that 81.48 % decrease in the thermal diffusivity corresponds to 59.1 % reduction in the peak heat gain for real wall material. This result reveals that thermal conductivity is a strong property such that any type of structure with higher thermal conductivity has higher heat gain values in a building.

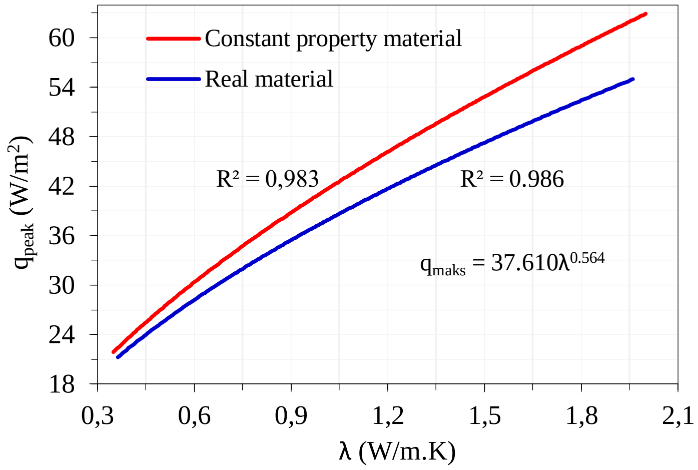


**Figure 7.** Comparison of the effect of the thermal conductivity on the peak heat gains through the walls for real material and constant property material.

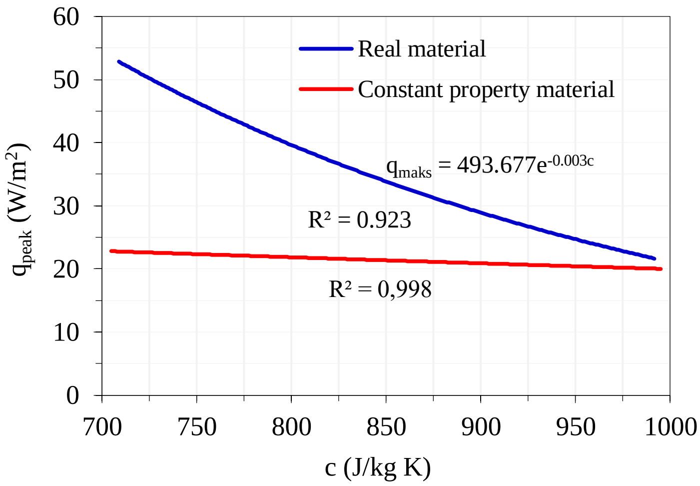


**Figure 8.** Comparison of the effect of the specific heat on the peak heat gains through the walls for real material and constant property material.

Specific heat is a property that measures the ability index of the material against temperature changes. A material having a high specific heat is useful in improving the temperature stability of a structure. It can be concluded from Eq. (11) that there is an inverse relationship between the specific heat and the density of wall material. Likewise, there is an inverse relationship between the peak heat gains and specific heat depicted in Figure 8. However, the decreasing tendencies for those wall materials are not the same. Since the thermal conductivity and density values are held constant for constant property wall material, an increase in the thermal diffusivity only results from the increase of the specific heat. From the results, it is shown that the peak heat gain decreases from 51.884 W/m$^2$ to 21.221 W/m$^2$ for real wall material with varying the specific heat values from 709.07 to 991.80 J/kg K. Hence, with a reduction in peak heat gains, the cooling capacity of the HVAC system can frequently be reduced.

In concrete or concrete masonry, heat capacity per thickness of a wall is determined by multiplying the wall mass per area (kg/m$^2$) by the specific heat (J/kg K) of the wall material. More simply, it is the product of a density and its specific heat. Figure 8 gives the relationship between heat capacity and peak heat gains for real and constant property wall materials with the same thicknesses of 24 cm (W1). Figure 8 indicates a very remarkable result that there is a nearly linear relationship between the peak heat gain and the heat capacity for real material. However, the degree of relationship between the peak heat gain versus heat capacity is much weaker than the other properties such as density and thermal conductivity. On the contrary, for constant property material, the constant thermal conductivity leads to a decrease in the thermal diffusivity with the increase of the heat capacity. Moreover, the variation of heat gains with respect to heat capacity is calculated and depicted in Figure 1b, and also presented in Refs. [13–17]. The results show that as the heat capacity goes to its maximum value, the heat gain value goes to its minimum value. These results can be theoretically correct; however, it is not a realistic situation. Figure 9 depicts that an increase in the density leads to an increase in the heat capacity of wall material, in spite of a decrease in the specific heat. In other words, an increase in density is greater than a decrease in the specific heat of materials, which also leads to an increase in the thermal conductivity as mentioned before. In general, heat capacity is not an effective property to indicate the thermal performance of building materials, since metals with very high thermal capacities also have very high thermal conductivities. Thereby, some insulation materials having very low thermal conductivities also have very low thermal capacities owing to their much lower density (Figure 3).

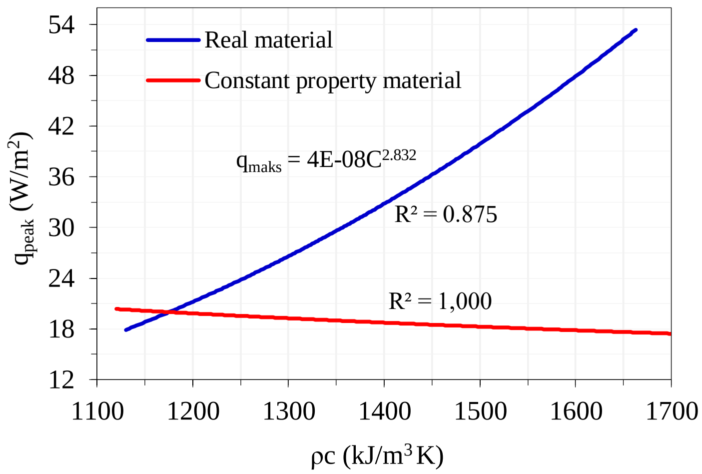


**Figure 9.** Comparison of the effect of the heat capacity on the peak heat gains through the walls for real material and constant property material.

In order to clearly see the effect of the heat capacity of wall samples on the heat gain, the hourly heat gain values, and the exterior surface temperature distributions across NC and EPC50 walls given in Ref. [22] with W1 configurations are plotted in Figure 10 due to the south direction for July 21. This figure reveals a relatively large heat gains for NC wall as compared with EPC50 wall having a lower value of heat capacity and thermal conductivity (the values of heat capacity and thermal conductivity for NC and EPC50 walls are 1662.83 kJ/m$^3$ K, 1.96 W/m K, and 1130 kJ/m$^3$ K, 0.363 W/m K, respectively). Due to the high thermal storage effect of the NC wall, while the temperature at the exterior surface is decreasing, the heat gain inside is still increasing. Thereby, for EPC, large heat gains are significantly reduced from the outer to the inner surface. After the heat gains across the EPC50 wall, the temperature on the inner plaster is maintained at a constant level of 24–27 ºC. In the case of NC wall, the variation of temperature is unsteady at the inner plaster and temperature is maintained at 25–31 ºC, which is higher than the design room value (24 °C) by about 7 °C. The inner temperature for structure NC reaches a maximum value of about 18:00 and a maximum value of about 21:00 for EPC50. The calculations reveal that the peak heat gain for EPC50 is 60.93 % smaller than that for NC. It is seen that NC is not a suitable wall material due to its higher heat gain for passive buildings. On the other hand, massive buildings (thermal mass) like Cathedrals (where the thickness of walls is about 1.0 m) can cope with a wide variation in heat and solar gains under the combination of natural ventilation and thermal inertia, and hence comfortable indoor conditions can be maintained without an HVAC system [29]. However, as explained above, a high thermal mass does not guarantee a comfortable environment and night ventilation is critical to avoid summer overheating, especially in Gaziantep, where the outer temperature sometimes exceeds 45 °C during the summer. If night ventilation is not provided, the walls may be constructed with appropriate thermal capacity and diffusivity to obtain thermal comfort conditions. Thus, the knowledge of the thermal behavior of a building material will provide the designer to select appropriate envelope forms to satisfy the changing requirements of a building interior space.

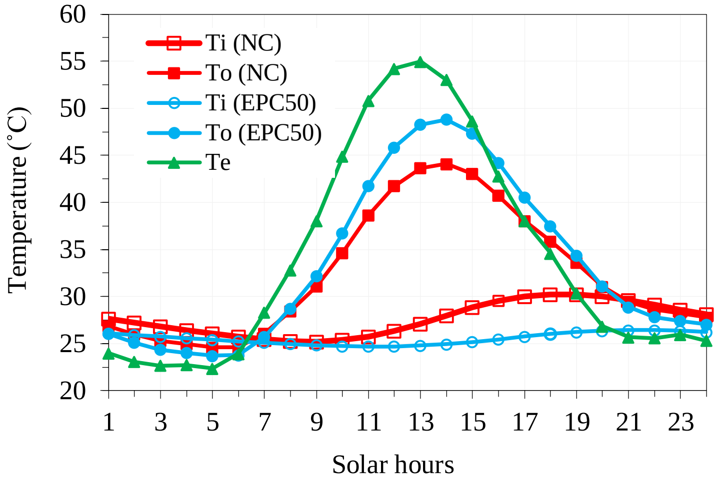


**Figure 10.** The distributions of the hourly inner surface, exterior surface and sol-air temperatures across NC and EPC50 walls with W1 configurations due to south direction.

Thermal diffusivity, *a* is a physical material property where materials with a high thermal diffusivity respond quickly to temperature changes and materials with low thermal diffusivity respond slowly to an imposed temperature difference [25]. An optimized exponential model represented in Eq. (12) for the thermal diffusivity identifies that the density as an important parameter in determining the thermal diffusivity, where the thermal diffusivity increases with the increasing of the density. However, some materials deviate from this rule: the largest deviations are observed by porous solids such as foams, as depicted in Figure 3. Although foams have low conductivities, their thermal diffusivities are not necessarily low due to their low densities. On the other hand, concrete and masonry are effective materials in terms of thermal mass in a building due to their low thermal diffusivities [25]. The effect of the thermal diffusivity values for real and constant property wall materials on the peak heat gains are presented in Figure 11. In this case, two different situations can be considered for the constant property wall material: the material with constant thermal conductivity and with constant heat capacity. Despite the fact that there is a linear relationship between the values of the peak heat gain and the diffusivity for all wall materials, their increasing tendencies are different. Whereas, the peak heat gains for real and constant conductivity wall materials are close to each other. This is owing to fact that there is a direct relationship between the thermal conductivity and diffusivity (Figure 2) for real material; thereby, the thermal conductivity values increase with the increase of thermal diffusivity at constant heat capacity for constant conductivity wall material.

On the other hand, for constant density wall material, a lower increase in the thermal diffusivity is due to the increase of the heat capacity at constant thermal conductivity. It can be concluded that thermal diffusivity is a significant property ($R^2$>0.98 for real wall material) that controls the temperature distribution and heat flux through a building structure as a function of time with the dependence of the thermal conductivity and heat capacity. The result shows that 73.82 % decrease in the thermal diffusivity corresponds to 59.1 % reduction in the peak heat gain for real wall material.

As stated before, thermal diffusivity is a significant property that controls the heat gains through a building structure as a function of time with dependence of thermal conductivity and heat capacity.

The peak heat gain for W1 increased with the increase of the thermal diffusivity. In this section, to demonstrate the effect of the thermal diffusivity on the heat gain values through different wall types, three wall assemblies are studied, which are given as W2, W3 and W4 with inner and outer insulation. The total thickness of each wall assemblies is 24 cm and their schematic representations are shown in Figure 5. The core of each wall assembly is selected as EPC50 wall and the peak heat gains through the wall assemblies with respect to the variation of the thermal diffusivity are calculated considering the relations obtained from an experimental study. As observed in Figure 11, a linear relationship exists between the peak heat gains and thermal diffusivity of wall assemblies since an increase in the thermal diffusivity leads to an increase in thermal conductivity. When Figure 11 and Figure 12 are analyzed together, huge reductions in the peak heat gains occur for the wall assembly W2, W3, and W4 with respect to the W1. This is because even though the core layer has higher thermal conductivity, the insulation layer diminishes the heat gains through the walls due to their low conductivities. Furthermore, it can be concluded that the variations of the thermal diffusivity versus the peak heat gain have a similar tendency for all wall configurations (W2, W3, and W4). The relationship between the thermal diffusivity and the peak heat gain for all roof configurations shows similar behavior to the relation for wall assemblies that their peak heat gains increased by increasing the thermal diffusivity.

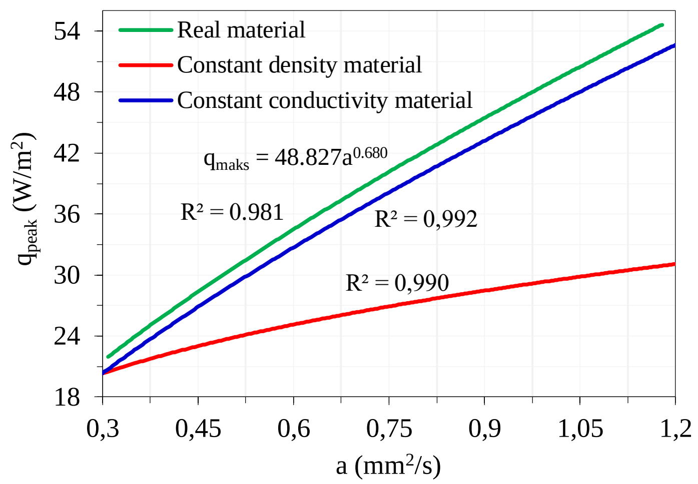


**Figure 11.** Comparison of the effect of the thermal diffusivity on the peak heat gains through the walls for real material and constant property material.

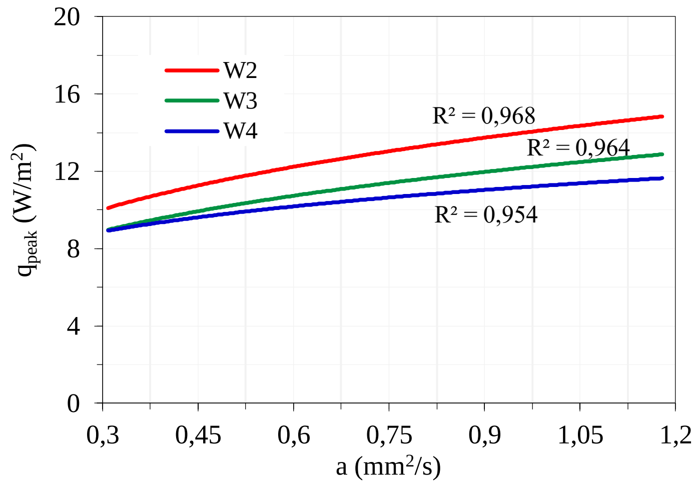


**Figure 12.** The peak heat gains through the wall assemblies with respect to the variation of the thermal diffusivity.

Figure 13 is depicted for comparing the peak heat gains through the roofs with respect to the variation of the thermal diffusivity. The roofs assemblies are named as R1, R2 and R3 with and without

EPS and their thicknesses are given as 17 cm. The calculated peak heat gains for roof assemblies are fairly higher than the gains for the wall due to the huge solar radiation incident on horizontal surfaces. From the results, the calculated peak heat gains are varied as 64.39 W/m$^2$ to 146.40 W/m$^2$, 25.39 W/m$^2$ to 31.33 W/m$^2$ and 50.84 W/m$^2$ to 86.85 W/m$^2$ for R1, R2 and R3; respectively, with the variation of the thermal diffusivity values from 0.309 mm/s$^2$ to 1.179 mm/s$^2$. R1 roof is thermally poor construction and commonly used in houses with one floor in Turkey. Especially in the summer season, high heat gains for R1 indicate a high level of cooling load and uncomfortable conditions. The increase of cooling load increases the capacity of the selected HVAC systems that also increases energy requirement and operation cost. When insulation material is used in the roof constructions (such as R2 and R3 roofs) in buildings, the huge heat gains through these structures will be diminished, thus thermal comfort conditions will be ensured by the minimum energy consumption and operation cost for both winter and summer seasons.

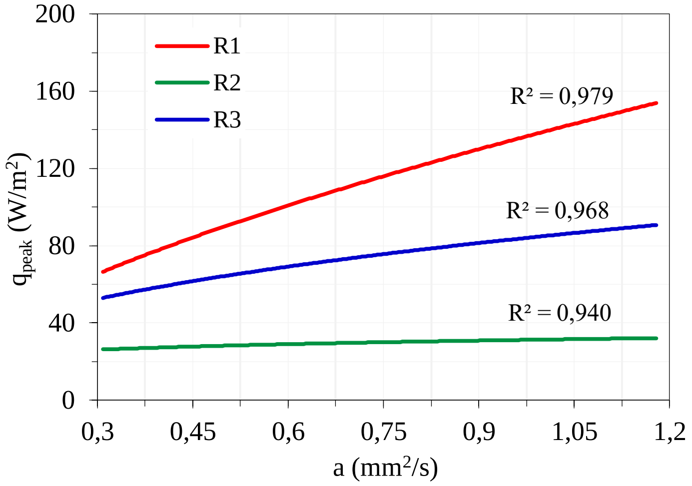


**Figure 13.** Comparison of the peak heat gains through the roofs with respect to the variation of the thermal diffusivity.

Figure 14 shows the peak heat gains with respect to different wall assemblies in the case of varying wall thickness with the same thermal property (the core of walls is considered as EPC50 wall material). Figure 14 depicts that there is an inverse exponential relationship between the peak heat gain and the wall thickness that the heat gain values for each wall decrease as the wall thickness increases. This is not surprising, as the wall thickness increases its heat storage capacity increases. The highest value of the peak heat gain is calculated as 11.92 W/m$^2$ for W1 (L=30 cm), the lowest one is calculated as 6.33 W/m$^2$ for the W3 wall (the wall with outer insulation layer). The results show that as the thickness of wall assemblies is varied from 10 to 30 cm (without increase the insulation thickness), the reductions in the peak heat gain value for W1, W2, W3, and W4 are 72.70 %, 63.13 %, 55.46 %, and 56.79 %, respectively. The results reveal that, especially in massive buildings, the thicker structure would absorb heat and delay the time when conditions would become uncomfortable. It can be concluded that when insulation is used in a wall, especially at the outside layer, thermal comfort conditions can be provided by the minimum energy consumption for both winter and summer seasons. Although the result of the present study is consistent well with Refs. [13–15] and [19], the thickness of the wall is not an effective parameter on heat gain due to the limitation of practical applications in passive or residential buildings. However, the result of the present study is useful for designing more effective massive constructions related to other energy-saving areas.

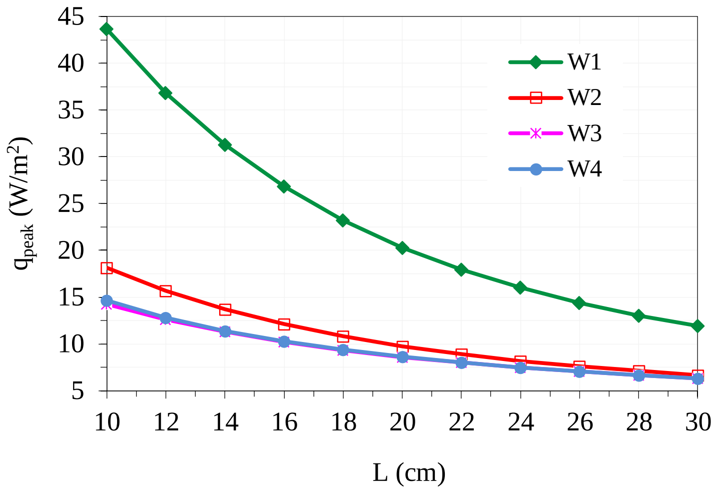


**Figure 14.** The peak heat gains with respect to different wall assemblies in the case of varying wall thickness with the same thermal property.

## 6. Conclusions

In this study, experimental and theoretical investigations were performed to establish the effect of each thermophysical property on heat gain through building wall and roof by taking account of a relationship between each thermophysical property. The main conclusions drawn are the following:

1. The use of relationships among the thermophysical properties in the calculations of dynamic thermal characteristics of building structures gives realistic results. However, those properties are taken as constant in the literature.
2. This result reveals that density, thermal conductivity, and diffusivity have a very profound effect on the heat gain. On the contrary, the degree of the relationship between heat gain and heat capacity is weaker than the other properties.
3. The results showed that the peak heat gains decreased from 51.884 W/m$^2$ to 21.221 W/m$^2$ for real wall material with varying the specific heat values from 709.07 to 991.80 J/kg K.
4. Despite the thickness of the wall has a superior effect on building heat gain, it is not an effective parameter due to the limitation of practical applications in passive or residential buildings.
5. Thanks to their insulation layers, huge reductions in the peak heat gains are observed for the wall assemblies of W2, W3, and W4 with respect to the W1. Moreover, the variations between the thermal diffusivity and the heat gain show a similar trend for all wall configurations (W1, W2, W3, and W4).
6. The most innovative point of this paper is that if the density of a building material is known, which can be measured with a relatively simple, rapid, and inexpensive way, the peak heat gains can be calculated easily for the selected walls by using expressions in Figure 6.

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