



## An Experimental Investigation of the Effect of Thermophysical Properties on Time Lag and Decrement Factor for Building Elements

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### Highlights

- The effects of thermophysical properties on TL and DF were investigated.
- TL and DF of walls were evaluated by Complex Finite Fourier Transform Technique.
- The approaches presented in the literature are not realistic in many cases.

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### Abstract

The time lag (TL) and decrement factor (DF) are essential for the heat storage capabilities of building elements, which strictly depend on the thermophysical properties of the elements. Many investigations are presented in literature arguing to find the influence of each thermophysical property on TL and DF by keeping the other properties constant. This study aims to investigate the effect of each property on TL and DF, utilizing relationships between the measurement values of the thermophysical properties of wall materials. Therefore, first, 132 new concrete wall samples were produced, and their thermophysical properties were tested. Secondly, TL and DF values for each building element are computed from the solution of the problem by Complex Finite Fourier Transform (CFFT) technique. Finally, a multivariate regression analysis has been performed, and the variations of each thermophysical property versus TL and DF are presented, and also the findings are compared with literature. The results show that each property alone (keeping the other properties constant) is not adequate to identify the thermal inertia and thermal performance of a wall element. Besides, 87.3 % decrease in thermal diffusivity corresponds to 6.03 h increase in the value of TL and 88.8 % decrease in value of DF; respectively, for W1 wall assembly.

## 1. INTRODUCTION

The world's energy demand is growing with increasing rapid development and population in emerging markets day by day. Furthermore, with the depletion of energy resources, our world is facing an energy crisis that can threaten our life and future. It is essential to reduce energy consumption that affects harmfully to the environmental and economic values. A significant amount of energy is consumed in the world by heating and cooling of buildings. By the way, building energy demand for the seasons is a loss or gain through the walls and the roofs, the windows, and types of equipment used. Besides, walls and roofs are responsible for a major fraction of the heating or cooling loads due to the heat loss or gains. Two important parameters, which are Time Lag (TL) and Decrement Factor (DF), indicate the magnitude of heat loss and gains and storage capabilities of the building elements. In literature, many studies have been presented to investigate the effective parameters of TL and DF values for a building. The parameters, which indicate the magnitude of heat loss and gains of a building, can be categorized as environmental parameters (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.) [1].

Sun et al. [2] studied the impact of the exterior temperature of a building on the TL and the DF. The researchers showed that the TL of the peaks of the parietal temperatures is not equal to the TL of the peaks when the wave of the ambient temperature is not sinusoidal. Mazzeo et al. [3] conducted a study to investigate the influence of the boundary conditions on TL and DF. They concluded that the presence of internal short-wave radiant loads increases the DF by order of magnitude and results in a delay of the maximum heat flow in a continuous regime. Gasparella et al. [4] recommended a modification of the transient thermal transmittance to calculate the TL and DF of a wall that was subject to sol–air temperature.

On the other hand, Ruivo et al. [5] numerically investigated the impact of the azimuth angle on the TL and DF. They found that azimuth has a significant impact on the TL, but a small impact on the DF. In another study, TL and DF have been calculated numerically for wall configurations having thermal insulation in two different climatic zones. The research results are useful for further development in the design of an optimum thermal insulation configuration, adjusted specific orientations, and coordinates [6]. Vijayalakshmi et al. [7] investigated the thermal properties of building wall elements in the indoor climate. Kaska et al. [8] developed an analytical technique to examine the TL and DF values of the multilayer elements. The analysis results of the study also were compared with experimental results. Stephan et al. [9] studied the effect of thermal insulation on thermal inertia utilizing TL and DF as temperature indicators. The results indicate that insulation appears to affect the TL but does not affect the DF. Ulgen [10] conducted theoretical and experimental studies on the assumption of periodic sinusoidal external boundary conditions, and also compared the obtained results of TL and DF. Also, several studies have been conducted on the effect of thickness and position of wall insulation on TL and DF by using both the numerical and mathematical methods. They pointed out that the thickness and position of thermal insulation have a very significant impact on the TL and DF [11-13].

Studies cited above indicate that the TL and DF depend on many factors, such as the exterior climate condition, building configuration, etc. for a building locating in a specific coordinate. Many investigations declared that the TL and DF values strongly depend on the thermophysical properties of the walls layer materials [10,14-17]. The essential thermophysical properties are thermal conductivity, specific heat, density, thickness, and thermal diffusivity for heat transfer processes in a building. Particularly, high specific heat capacity is useful for the associated ability to retain heat. Besides, low thermal conductivity is useful for the appropriate ability to provide insulation [18]. The thermophysical properties of a building wall or roof material are highly affected by microelement, composition, moisture content, and porosity [19]. On the other hand, many studies have shown that there is a relationship between the thermophysical properties of building materials [20-23].

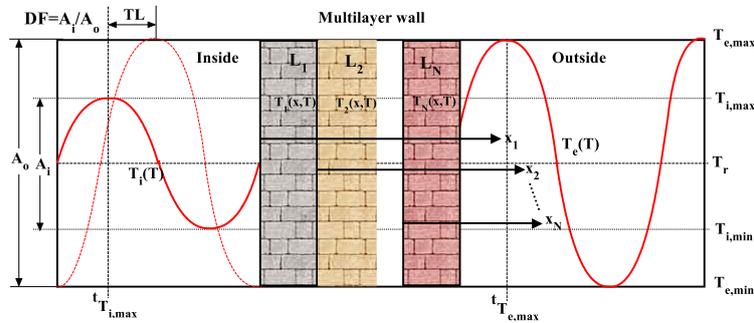
Although many studies have been conducted to investigate the effect of the thermophysical properties of opaque components of the building element on thermal parameters such as TL and DF, etc., the current practices ignore the relationship between these properties. Hence, some unrealistic [14,15], inconclusive [16,17] and contradictory results [24,25] exist in the literature. Since no research has been done to examine the validity of these results in detail for realistic cases (in their theoretical analyses, the thermophysical properties of building elements have not been considered as independent of each other), there is still insufficient information about the effect of thermal properties of building materials on TL and DF.

In the study, the time lag (TL) and decrement factor (DF) for building wall materials are evaluated by using measurement values of the thermophysical properties of the building elements. In this regard, 132 new concrete wall samples were produced, and their thermophysical properties were measured in accordance with EN and ASTM standards. In order to evaluate possible relations among the measurement data, a multivariate regression analysis has been carried out. In a theoretical study, the highest and lowest inner surface temperatures for a building element, and their periods are computed by using a solution of the periodic heat transfer problem during design day for Batman. Then, the TL and DF values of each sample are calculated and compared with the literature.

## 2. THE SOLUTION OF THE HEAT TRANSFER PROBLEM

Time lag (TL) and decrement factor (DF) are known parameters to determine the heat storage capabilities of the building elements. The TL and DF are given as function for the highest and lowest inside surface and

sol-air temperatures and their times for an element. Therefore, the highest temperatures and their times should be found by solving a conduction heat transfer problem. The heat transfer problem and its solution procedure for finding the temperatures are given in this section. A schematic view of a multilayer building wall or roof, including a finite number of layers, as well as the definition of DF and TL, are shown in Figure 1.



**Figure 1.** A view of a multilayer wall or flat roof with the definition of the time lag and decrement factor

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

- a) there is no internal heat generation in any wall layer,
- b) the resistance of the interface between the layers is neglected,
- c) the combined convection (both radiation and convection) coefficients are constant.

By using those assumptions, the transient heat transfer problem for a building element is given by the following differential equations under boundary conditions:

$$\frac{\partial^2 T_n}{\partial x_n^2} = \frac{1}{a_n} \frac{\partial T_n}{\partial t} \quad 1 \leq n \leq N \tag{1}$$

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

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

$$T(x_{n-1} = L_{n-1}) = T(x_n = 0) \quad \text{for } 2 \leq n \leq N \tag{4}$$

$$-\lambda_N \frac{\partial T_N}{\partial x_N} = h_o [T_N - T_e(t)] \quad \text{at } x_N = L_N \tag{5}$$

where  $n$  corresponds to the layer number, i.e.,  $n=1, 2, \dots, N$ ,  $\alpha_s$  is the absorptivity of the surface,  $\varepsilon$  is the hemispherical emissivity of the surface,  $h_i$  and  $h_o$  are the combined convection heat transfer coefficients at the interior and exterior surfaces, respectively. The periodicity condition,  $T_n(x_n, t) = T_n(x_n, t + p)$  must be applied to the problem as the temporal condition. The transient heat transfer problem given by Equations (1)–(5) will be converted to dimensionless form by following dimensionless variables:

$$\begin{aligned} z_n &= \frac{x_n}{L_n}, \quad S_{n-1,n} = \frac{\lambda_{n-1} L_n}{\lambda_n L_{n-1}}, \quad b_i = \frac{h_i L_1}{\lambda_1}, \quad b_o = \frac{h_o L_n}{\lambda_n}, \quad \tau_n = \frac{a_n t}{L_n^2}, \\ \tau_{np} &= \frac{a_n p}{L_n^2}, \quad \tau = \frac{t}{p}, \quad I_T(\tau_n) = \frac{\alpha_s L_n}{\lambda_n} I_T(t) \quad p = 24 \text{ h.} \end{aligned} \tag{6}$$

The resulting dimensionless formulation is

$$\frac{\partial^2 T_n}{\partial z_n^2} = \frac{\partial T_n}{\partial \tau_n} \quad 1 \leq n \leq N \quad (7)$$

$$(T_i - T_1) b_i = -\frac{\partial T_1}{\partial z_1} \quad \text{at } z_1 = 0 \quad (8)$$

$$S_{n-1,n} \frac{\partial T_{(n-1)}}{\partial z_{n-1}} (z_{n-1} = 1) = \frac{\partial T_n}{\partial z_n} (z_n = 0) \quad 2 \leq n \leq N \quad (9)$$

$$T_{n-1} (z_{n-1} = 1) = T_n (z_n = 0) \quad \text{for } 2 \leq n \leq N \quad (10)$$

$$-\frac{\partial T_N}{\partial z_N} = b_o [T_N - T_e(\tau_n)] \quad \text{at } z_N = 1. \quad (11)$$

The periodicity condition now takes a new form of  $T_n(z_n, t) = T_n(z_n, \tau + 1)$ . The problem given by Equations (7)-(11) will be solved to obtain a transient solution by an application of the Complex Finite Fourier Transform Technique (CFFT):

$$T_{nj}(z_n) = \int_{-1/2}^{1/2} T_n(z_n, \tau) e^{-i\omega_j \tau} d\tau. \quad (12)$$

The transformed problem is given by Equation (12) is applied to the dimensionless formulation indicated by Equations (7)-(11) using constant room temperature. The solution of the heat-transfer problem is detailed in Yumrutas et al. [26], and the closed solution of Equation (12) is presented here:

$$T_{n0}(z_n) = A_n z_n + B_n \quad \text{for } j=0 \quad (13)$$

$$T_{nj}(z_n) = C_{nj} \sinh(\gamma_{nj} z_n) + D_{nj} \cosh(\gamma_{nj} z_n) \quad \gamma_{nj} = \sqrt{i\omega_{nj}} \quad \text{for } j \neq 0 \quad (14)$$

where  $A_n, B_n, C_{nj}$ , and  $D_{nj}$  are unknown variables gathered from the boundary conditions given by Equations (8)-(11). The closed solution of the problem is presented as:

$$T_n(z_n, \tau) = \sum_{j=-M}^M T_{nj}(z_n) e^{i\omega_j \tau} \quad \omega_j = 2\pi j \quad (15)$$

where  $T_n(z_n, \tau)$  is the temperature profile for the wall or roof.  $M$  is a large number, and it is generally taken as 60. In order to calculate the TL and DF, the interior surface temperature of the wall can be obtained by Equation (15) for  $n=1$  and  $z_1=0$  and expressed as:

$$T_1(0, \tau) = \sum_{j=-M}^M T_{1j}(0) e^{i\omega_j \tau}. \quad (16)$$

## 2.1. Sol-air Temperature

One boundary condition in Equations (5) and (11) for the heat transfer problem formulation is given as a function of sol-air temperature,  $T_e(t)$ , which involves the effect of solar radiation and is presented as:

$$T_e(t) = T_a(t) + \frac{\alpha_s I_T(t)}{h_o} - \frac{\varepsilon \Delta R}{h_o} \quad \text{at } x_N = L_N. \quad (17)$$

The sol-air temperature,  $T_e(t)$  given by Equation (17), can be expressed as transformed form by applying the CFFT technique

$$T_{eN}(1, \tau) = \sum_{j=-M}^M T_{eNj}(1) e^{i v_j \tau} \quad (18)$$

where  $T_a(t)$  is ambient air temperature,  $\alpha_s$  is the absorptance coefficient for the exterior surface of the wall. The last term in Equation (17),  $\varepsilon \Delta R / h_o$  is defined as the correction factor ASHRAE [27], which is specified to be 4°C for horizontal surfaces facing up, and is specified to be 0°C for vertical surfaces.  $I_T(t)$  is the hourly solar radiation incident on a tilted surface and is expressed as the total of the beam,  $I_b(t)$ , diffuse  $I_d(t)$ , and reflected radiation,  $I_r(t)$  [28]

$$I_T(t) = I_b(t) R_b + I_d(t) \left( \frac{1 + \cos \beta}{2} \right) + I_r(t) \rho_g \left( \frac{1 - \cos \beta}{2} \right) \quad (19)$$

where  $\rho_g$  is ground reflectance (taken as 0.2 in the present study).  $R_b$  is a geometric factor and is defined as the ratio of beam radiation on a tilted surface to that on a horizontal surface:

$$R_b = \frac{\cos \delta \sin \varphi \cos \gamma \cos \omega + \cos \delta \sin \gamma \sin \omega - \sin \delta \cos \varphi \cos \gamma}{\cos \varphi \cos \delta \cos \omega + \sin \varphi \sin \delta} \quad (20)$$

where  $\delta$ ,  $\omega$ ,  $\gamma$  and  $\phi$  are the declination, hour, surface azimuth, and latitude angles, respectively.

## 2.2. Calculation of the Time Lag and Decrement Factor

The Time Lag (TL) and the Decrement Factor (DF) are essential characteristics for building elements to determine their heat storage capabilities. The TL is defined as the time required for a heatwave to propagate through a building element from the exterior to the interior surface. The DF is defined as the decreasing proportion of its temperature amplitude during a periodic wave penetrating through a building element. The schematic presentation of the TL and DF is indicated in Figure 1, and their definitions are obtained using the relations:

$$TL = t_{T_{i,max}} - t_{T_{e,max}} \quad (21)$$

$$DF = \frac{A_i}{A_o} = \frac{T_{i,max} - T_{i,min}}{T_{e,max} - T_{e,min}} \quad (22)$$

where  $t_{T_{i,max}}$  and  $t_{T_{e,max}}$  represent the times when interior surface and sol-air temperatures are at their maximums, respectively. Besides,  $T_{i,max}$ ,  $T_{e,max}$ ,  $T_{i,min}$ , and  $T_{e,min}$  are the maximum and the minimum temperatures on both interior surface and sol-air temperatures, respectively. When derivatives of Equations (16) and (18) are set equal to zero, the highest, the lowest inner surface and sol-air temperatures, as well as their periods, can be determined, respectively.

## 2.3. Comparison of Time Lag and Decrement Factor

In order to show the reliability of the present study, TL and DF values obtained by the previous method are compared with Mackey and Wright's method [29,30], and Luo et al.'s [31] model. Mackey and Wright developed a simplified method to calculate the temperature of the interior surface of the homogeneous [29] and composite wall or roofs [30]. The simplified method provides accurate results with external excitation.

Table 1 shows the comparison of TL and DF values for the selected wall types in Mackey and Wright [30], Luo et al. [31], and those obtained from the present study. When the results are compared to each other, it is found that the maximum relative error between the results of the present study (0.45% for DF and 3.85%

for TL) and those of Mackey and Wright and Luo et al. (1.55% for DF and 4.57% for TL) is very small. The results show that the TL and DF values calculated by the method given in this study are in good agreement with the results of Luo et al. and Mackey and Wright, hence showing the reliability of the model used in the present study.

**Table 1.** Comparison of the time lag and decrement factor for selected walls

| Wall number | Layer     | Mackey and Wright method |        | Luo et al. volume method |        | Luo et al. response factor method |        | Present paper by CFFT method |        |
|-------------|-----------|--------------------------|--------|--------------------------|--------|-----------------------------------|--------|------------------------------|--------|
|             |           | TL (hr)                  | DF     | TL (hr)                  | DF     | TL (hr)                           | DF     | TL (hr)                      | DF     |
| 1           | (2-layer) | 4.52                     | 0.1613 | 4.43                     | 0.1588 | 4.51                              | 0.1611 | 4.46                         | 0.1610 |
| 26          | (2-layer) | 15.8                     | 0.0147 | 15.77                    | 0.0146 | 15.79                             | 0.0148 | 15.79                        | 0.0148 |
| 27          | (2-layer) | 24                       | 0.0019 | 23.77                    | 0.0019 | 23.89                             | 0.0019 | 23.88                        | 0.0019 |
| 28          | (2-layer) | 8.47                     | 0.0658 | 8.43                     | 0.0661 | 8.49                              | 0.0663 | 8.43                         | 0.0663 |
| 29          | (2-layer) | 12.6                     | 0.0249 | 12.6                     | 0.0249 | 12.56                             | 0.0252 | 12.53                        | 0.0251 |
| 31          | (3-layer) | 3.28                     | 0.2142 | 3.43                     | 0.2145 | 3.38                              | 0.2149 | 3.25                         | 0.2148 |
| 32          | (3-layer) | 12.2                     | 0.0219 | 12.27                    | 0.0218 | 12.22                             | 0.022  | 12.18                        | 0.0219 |
| 33          | (3-layer) | 4.6                      | 0.1612 | 4.6                      | 0.1608 | 4.53                              | 0.1613 | 4.46                         | 0.1613 |
| 34          | (3-layer) | 3.6                      | 0.1858 | 3.6                      | 0.186  | 3.55                              | 0.1863 | 3.49                         | 0.1862 |

### 3. EXPERIMENTAL STUDY

Thermophysical properties of building elements are essential for evaluating the thermal performance of a building. Calculation of TL and DF of a wall depends on its thermophysical properties such as density, thermal conductivity, and specific heat; however, no study uses relationships between the properties of the materials. In literature, to find the effect of each property on heat transfer or TL and DF, one of these properties is changed, and the others are kept constant. In this study, thermophysical properties obtained 132 different building elements are used to estimate TL and DF with respect to these properties.

#### 3.1. Materials, Test Procedures and Correlations from the Test Data

In the present study, experimental research was carried out to establish the relationships between the thermophysical properties by performing a set of consistent tests. In this regard, 132 wall samples were produced, and their thermophysical properties tests were performed. The chemical composition and physical properties of the materials, as well as the preparation of concrete mixtures, are explained in detail in ref. [32]. The thermophysical tests were performed by the Transient Plane Source (TPS) technique, according to EN 12667 [33]. The advantage of the TPS method is that some of them give a full set of thermophysical properties within a rapid measurement. The range values and tolerance limits of the TPS device for the measured parameters and thermophysical properties of produced samples are presented in Table 2, respectively.

**Table 2.** Values of device range for measuring parameters

| Measurement          | Measurement range                                    | Accuracy                                   |
|----------------------|--|--|
| Thermal conductivity | 0.015–6 W/m. K                                       | 5 % of reading + 0.001 W/mK                |
| Heat capacity        | $4 \times 10^4 - 4 \times 10^6$ J/m <sup>3</sup> . K | 15 % of reading + 1.103 J/m <sup>3</sup> K |

In the study, multivariate regression is performed on the dataset of tested samples using the free statistical software in Microsoft Excel. The regression analysis aims to evaluate possible correlations between the measurement values of the thermophysical properties of building wall elements. The accuracy of the regression model is determined by the square of the multiple determination coefficient,  $R^2$ . When the value of  $R^2$  is close to unity, the better model fits the data. The curves for series of the mixtures are plotted, and linear and logarithmic curves generally present the best-fit curve for each tested sample.

The ranges of the tested samples' property values are large enough to cover most common elements in building construction that can be used for both structural (beam, column) and non-structural (wall, roof) purposes. However, an important question remains: "What will the situations be for different building materials and the properties out of these ranges?" In order to give a correct answer, it is required to make a comparison between the relations obtained from test samples and different building materials in terms of thermophysical properties. The relations obtained from tested samples and a comparison between a comprehensive list of building materials [34] are presented in Figures 2 and 3, respectively.

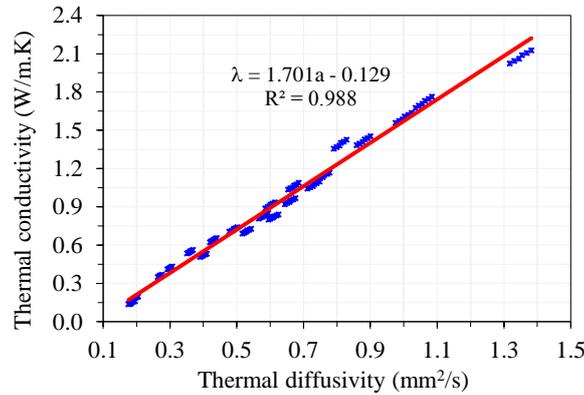


Figure 2. Relationship between the thermal diffusivity and thermal conductivity

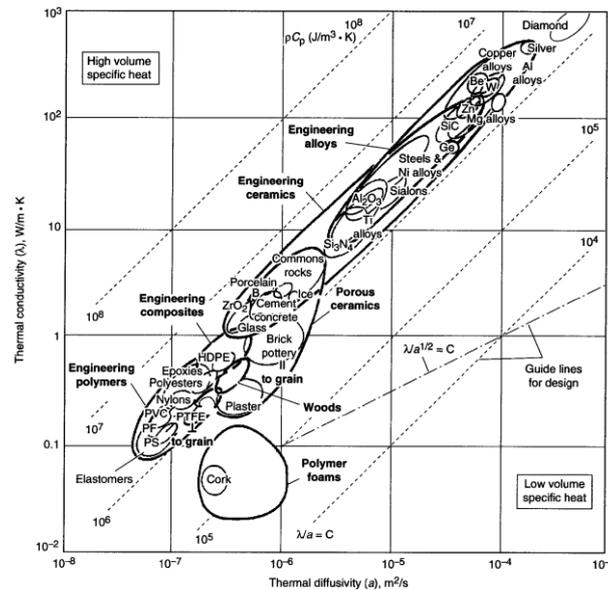


Figure 3. A comprehensive list of building materials: Thermal conductivity,  $\lambda$ , plotted against thermal diffusivity,  $a$ , for room temperature [34]

It can be concluded that the relations obtained from this study proved a similar tendency to those relations reported in the literature and covered all other building materials. However, the expressions should be used with care for the properties that fall outside the tested range.

### 3.2. The relationships between the thermophysical properties and TL&DF

In order to recognize the nature of the relationships between TL and DF and elements depend on its thermal properties, it is required to investigate them within the representative set of samples of different thermal properties. It would be an explicit functional dependence, but rather a strong correlation. It is shown from the Equations (21) and (22) that TL and DF depend on two temperatures: the maximum and the minimum sol-air and interior surface temperatures and their periods. As mentioned above, the sol-air and inside surface temperatures are functions of environmental parameters (solar radiation incident, ambient air temperature, ventilation, etc.), design parameters (orientation, solar absorptivity, emissivity, etc.) and

thermophysical properties (thermal conductivity, specific heat, density, thickness, etc.). When environmental and design parameters are held constant, TL and DF only depend on the thermophysical properties of a building element. To establish the relationship between each property on TL and DF, first, the values of TL and DF are calculated for each wall assembly with different thermophysical properties. Then, the curve for calculated data points versus each thermophysical property is plotted, and a best-fit curve is selected for the plotted data points in the figures.

#### 4. COMPUTATIONAL PROCEDURE

An accurate calculation of the transient heat transfer problem for an element is quite complicated and time-consuming due to both thermal storage effects of the building's thermal mass and ever-changing climatic conditions. Hence, a program in MATLAB was prepared to evaluate the hourly solar radiation incident on horizontal and tilted surfaces, heat fluxes through to elements, and the hourly temperature variations in those elements for a given climatic data. The following parameters are used in the program as inputs: the hourly solar radiation incident on the horizontal surface, hourly ambient, and design air temperatures and thermophysical properties of the building elements. First, the hourly solar radiation incident on a tilted surface is computed by using Equations (19) and (20). Then, the inner surface and sol-air temperatures of the building elements are computed by using the periodic solution given in Equations (16) and (18). The climatic data were obtained in Batman (latitude: 37.79 °N, longitude: 41.06 °E) by the measured temperatures between 2006 and 2016 on July 21. The coefficients of heat transfer at the interior, exterior surfaces, and room temperature were used in the calculations as 8.3 W/m<sup>2</sup>°C, 17 W/m<sup>2</sup>°C and 24 °C, respectively. Solar absorptivity ( $\alpha_s$  in Equation (6)) which depends on the external face color of a building envelope, is generally assumed to be 0.8 (dark-colored surface).

#### 5. RESULTS AND DISCUSSIONS

In this section, both experimental and theoretical results are presented to estimate the degree of the relationship between each thermophysical property and TL& DF for different wall configurations shown in Figure 4. The first wall assembly (W1) is a wall without insulation. All results for the W1 are given in Section 5.1. The second (W2) and the third wall assembly (W3) are walls with insulations. The effect of insulation on TL and DF is given in section 5.2. Furthermore, the expressions obtained from the analysis are presented in each figure.

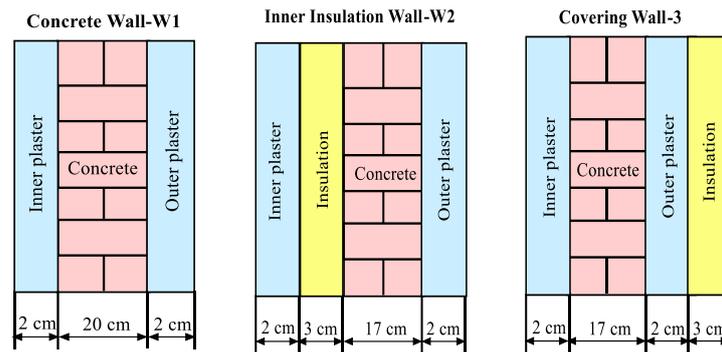
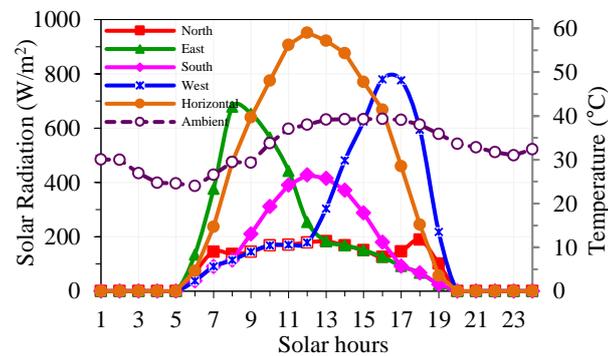


Figure 4. Configuration of the walls used in the study

##### 5.1. The Influence of the Thermophysical Properties on TL and DF

The south wall is responsible for the most heat gain among the wall elements since it receives most of the solar radiation. Hence, the investigations are performed for the walls facing south orientations under a non-sinusoidal periodical external environment. In order to obtain temperature distributions for the inner surfaces, it is necessary to know the hourly ambient air temperature and the sol-air temperature values for design day. The solar radiation incident (W/m<sup>2</sup>) on exterior surfaces due to main directions and variation of hourly ambient air temperatures are indicated in Figure 5 for the city of Batman. In view of that, by using

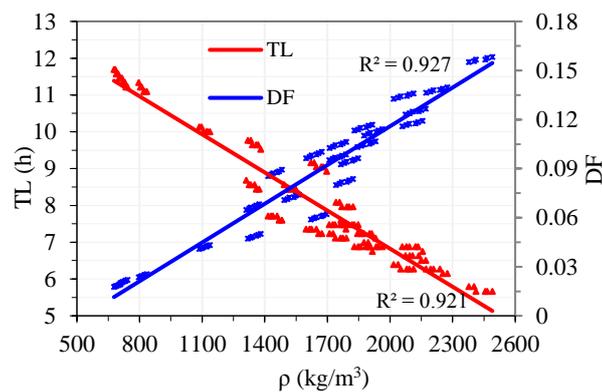
non-sinusoidal (actual) sol-air temperature values and taking certain (inconstant) thermophysical properties, the effect of each on the TL&DF values has been investigated.



**Figure 5.** The solar radiation incident on exterior surfaces due to main directions and variation of hourly ambient air temperatures

### 5.1.1 Influence of the density on TL and DF

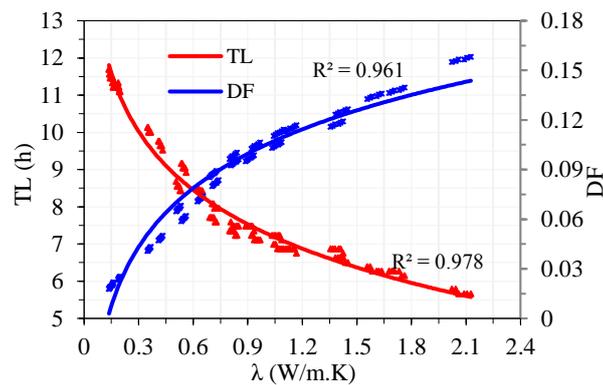
Figure 6 presents the effect of density on TL and DF for south-facing elements. This figure indicates that a direct relationship exists between the DF and density ( $R^2=0.93$ ), and an inverse relationship exists between the TL and density ( $R^2=0.92$ ) as DF increases and TL decreases with the increasing amount of density. This is because a linear relationship exists among density, thermal conductivity, and thermal diffusivity, respectively [20]. Therefore, density is a dominant property that affects the thermal inertia parameters differently, and the associated changes in its thermal inertia parameters have opposing effects on the time lag. The results show that 72.8 % reduction in density corresponds to a 6 h increase of TL and 88.8 % reduction in DF; respectively, for W1 wall assembly with a thickness of 24 cm. On the contrary, in a study of Kontoleon et al. [17], the variations of TL and DF are demonstrated for the IC wall assembly by changing the concrete density, while keeping the thermal conductivity constant. Because the density of the wall is regarded as independent from other properties, in their study, an increase in concrete density leads to a decrease in DF and an increase in TL.



**Figure 6.** Variation of the time lag and decrement factor with the density of concrete walls

### 5.1.2 Influence of the thermal conductivity on TL and DF

Thermal conductivity variations of wall samples show a similar tendency to their density variations. It is depicted in Figure 7 that TL and DF of the samples develop logarithmic functions with  $R^2=0.98$  and  $R^2=0.96$ , respectively. As a result, the thermal conductivity is a strong property such that any element with higher thermal conductivity has higher DF and lower TL values in a building. However, as stated before, the thermal conductivity is not the only property to characterize the thermal inertia of building walls or roofs. The results show that the maximum difference in TL values is about 6.03 h, and the maximum percentage of reduction in DF values is 88.8 % for concrete samples with varying average thermal conductivity values from 0.137 to 2.127 W/m.K.

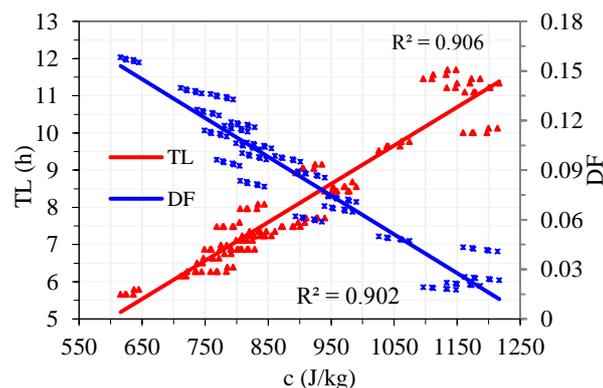


**Figure 7.** Variation of the time lag and decrement factor with the thermal conductivity of concrete walls

### 5.1.3 Influence of the specific heat and heat capacity on TL and DF

Specific heat is a property that measures the index of the capability of a sample with temperature changes. A sample with high specific heat is beneficial for increasing the temperature stability of an element. It can be concluded from [20] that specific heat of concrete is inversely proportional to its density. As seen from Figure 8, there is a linear relationship between TL and specific heat, and an inverse linear relationship exists between DF and specific heat. As specific heat values increase, not only do the DF values increase, but the TL also increases, which leads to an improvement in the element's temperature stability. This can be expected because if the specific heat is too high, the stored heat in the envelope can maintain an almost constant internal wall temperature. The results show that 49.4 % increase in specific heat corresponds to 50 % increase in the value of TL and 85.2 % reduction in the value of DF; respectively, for W1 wall assembly.

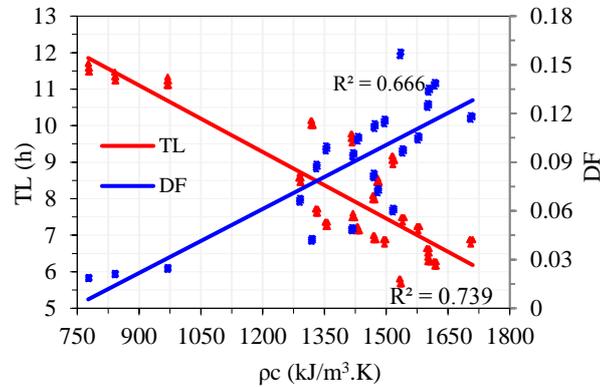
In a masonry structure, the heat capacity is determined by multiplying the wall mass per area ( $\text{kg/m}^2$ ) by the specific heat ( $\text{J/kg} \cdot \text{K}$ ) and the thickness (m) of the wall material. More simply, it is the product of a density and its specific heat. Figure 9 gives the relationships between TL vs. heat capacity and DF vs. heat capacity for the same wall thicknesses (24 cm).



**Figure 8.** The effect of the specific heat of concrete walls on the time lag and decrement factor

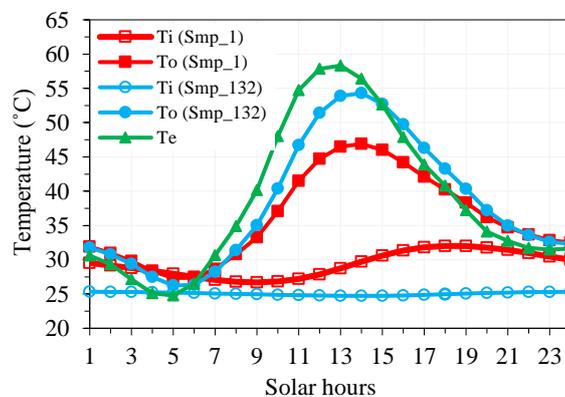
As seen in Figure 9, there is an inverse linear relationship between TL vs. heat capacity and a linear relationship between DF vs. heat capacity. However, the degree of relationship is much weaker than the properties such as density and thermal conductivity. [14,15], [24] and [25] claim that there is a direct relationship between TL vs. heat capacity, and there is an inverse relationship between DF vs. heat capacity. Moreover, the fact that as heat capacity goes to its maximum value, the DF goes to its minimum value. The results can be theoretically correct; however, it is not a realistic situation. As mentioned before, Oktay et al. [20] and other studies concluded that there is an inverse relationship between specific heat and density; thereby, there is a direct relationship between density and thermal conductivity. Furthermore, it is evident from Figure 9 and [20] that an increase in density leads to an increase in the heat capacity of wall material,

despite a decrease in specific heat; in other words, an increase in density values is more significant than a decrease in specific heat values of materials, which also leads to an increase in the thermal conductivity. In general, heat capacity is not an effective property to determine the variations in each property of an element, since some insulation materials (polyurethane, formaldehyde) have very low thermal conductivities, and the heat capacities of them are also very low owing to their much lower density. Thereby, metals have very high thermal capacities, and the thermal conductivities of them are also very high. (Figure 3).



**Figure 9.** Variation of the time lag and decrement factor with the heat capacity of concrete walls

To clearly see the effect of the heat capacity of concrete wall samples on TL and DF, the inner and outer surface temperature distributions across Sample\_1 and Sample\_132 walls with W1 configurations are plotted in Figure 10 due to south direction at various time intervals for July 21. This figure reveals a relatively large inner temperature fluctuation for Sample\_1 wall as compared with Sample\_132 wall having lower heat capacity and thermal conductivity (the average values of heat capacity and thermal conductivity for Sample\_1 and Sample\_132 walls are 1534.19 kJ/m<sup>3</sup>.K, 2.127 W/m.K, and 777.93 kJ/m<sup>3</sup>.K, 0.137 W/m.K, respectively). Because of the high thermal storage effect of Sample\_1 wall, while the temperature at the exterior surface is decreasing, the temperature inside is still increasing. Whereas, for the Sample\_132 wall, large heat fluxes are significantly reduced from the exterior to the interior surface. After heat fluxes across the Sample\_132 wall, the temperature on the interior plaster is maintained at a constant level of 24-26 °C. In the case of the Sample\_1 wall, the variation of the temperature is unsteady at the interior plaster, and the temperature is maintained at 26-32 °C, which is higher than the design room value (24 °C) by about 8 °C. The inner temperature for element Sample\_1 reaches a maximum value of about 18:00 and a maximum value of about 22:00 for Sample\_132. As stated before, the DF and TL are two parameters that are related to the magnitude of the cooling load due to heat gain. The calculations reveal that the difference in TL values between Sample\_1 and Sample\_132 wall is about 6.03 h, and the DF value for Sample\_132 is 88.8 % smaller than that for Sample\_1. Hence, using the Sample\_1 in a wall construction is not appropriate due to its higher cooling load.



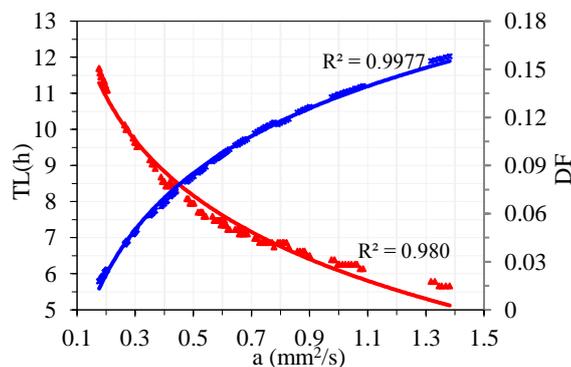
**Figure 10.** Temperature distributions across the Sample\_1 and Sample\_132 walls due to the south direction at various time intervals

On the other hand, massive buildings (thermal mass) like Cathedrals (where the thickness of walls is about 1.00 m) can cope with a wide variation in heat and solar gains under the combination of natural ventilation and thermal inertia, and hence comfortable conditions can be achieved without using an HVAC system [35]. 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 Batman, where the ambient air temperature rarely exceeds 45 °C during the summer. If night ventilation cannot be assured, the walls may be built so as to have appropriate thermal storage capacity and thermal diffusivity to obtain suitable TL and DF. Thus, the knowledge of the thermal behavior of an envelope will provide to the designer to select suitable envelope types to suit the fractional requirements of a building interior space.

#### 5.1.4 Influence of the thermal diffusivity on TL and DF

Thermal diffusivity is a physical material property where materials having a high thermal diffusivity respond quickly to changes in temperature, and materials with low thermal diffusivity respond slowly to an imposed temperature difference [23]. In [20], an optimized exponential model has been represented for the thermal diffusivity of the concrete samples. This statistical approach identifies the density as an important property in determining the diffusivity, which increases with increasing of the density. Besides, an increase in density leads to an increase in the thermal conductivity of wall material, and hence the results reveal that there is a direct relationship between thermal conductivity and diffusivity, as shown in Figure 2. However, some materials deviate from this rule: the most considerable deviations are indicated by porous solids such as foams and woods, as shown in Figure 3. Since they contain fewer atoms per unit volume, and  $\rho c$  is low. However, foams have low conductivities; their thermal diffusivities are not necessarily low. On the other hand, concrete is a useful thermal mass element because of its low diffusivity [23].

The effect of thermal diffusivity values of the walls on TL and DF are presented in Figure 11. This figure demonstrates that there is a pretty strong relationship between values of TL, DF, and thermal diffusivity: as thermal diffusivity decreases, the DF decreases, and TL increases. The results show that thermal diffusivity is the most effective property ( $R^2 > 0.98$  for both TL and DF) that controls the temperature distribution and heat flux through a building element as a function of time with the dependence of thermal conductivity and heat capacity.



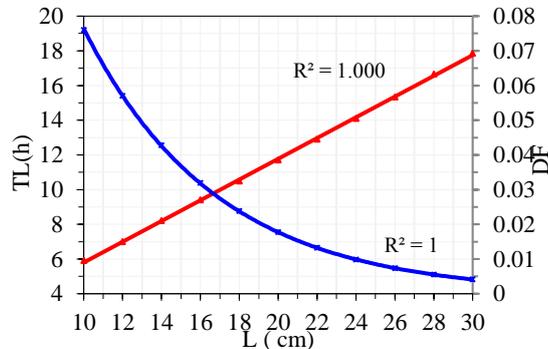
**Figure 11.** The effect of the thermal diffusivity of concrete walls on the time lag and decrement factor

The result shows that 87.3 % decrease in thermal diffusivity corresponds to 6.03 h increase in the value of TL and 88.8 % decrease in value of DF; respectively, for W1 wall assembly. As a result, constructing a building element with low thermal diffusivity is another effective way to control the heat transmission rate and, after that, reduce the consumption of energy.

#### 5.1.5 Influence of the thickness of a wall on TL and DF

Figure 12 shows the TL and DF values varying wall thickness with the same thermal property. As seen in Figure 12, there is a linear relation ( $R^2=1$ ) between TL and wall thickness, and an exponential ( $R^2=1$ )

relationship exists between DF and wall thickness. It is expected, as the wall thickness increases, its heat storage capacity increases (heat capacity of a masonry wall is calculated by multiplying the wall mass per area by the thickness of the wall material and by the specific heat). As the thickness of the wall reaches its maximum value, DF exponentially goes to zero, and TL goes to infinity. The results show that the thickness of a wall (Sample\_132 wall with W1 configuration) is increased from 10 to 30 cm, the increase in TL value is about 11.94 h, and the reduction in DF value is 94.6 %.

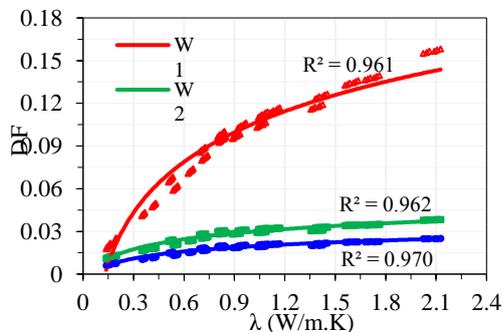


**Figure 12.** Variation of the time lag and decrement factor with the thickness of multilayer walls

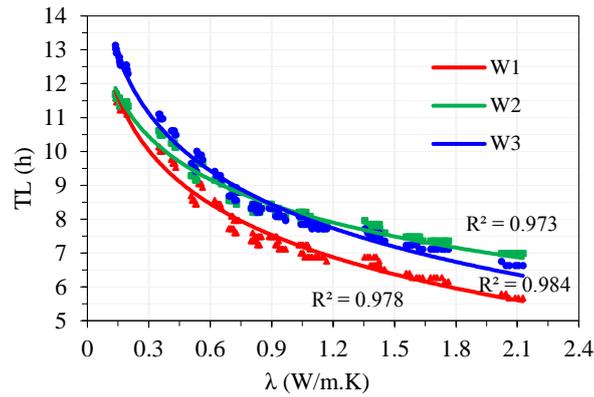
The results reveal that, especially in massive buildings, the thicker element would absorb heat and delay the time when conditions would become uncomfortable. Although the obtained result is consistent well with refs. [14,15], [24], and [36], the thickness of the wall material is not particularly deterministic in terms of TL and DF due to limits of practical applications in passive or residential buildings.

## 5.2. Influence of the Insulation on TL And DF

In order to demonstrate the effect of insulation layer on TL and DF, three wall assemblies are studied, which are wall assembly without insulation (W1) and wall assemblies insulated with EPS ( $\lambda = 0.038$  W/m. K,  $\rho = 18$  kg/m<sup>3</sup>,  $c = 1500$  J/kg. K, and  $a = 1.40$  mm<sup>2</sup>/s) are given as W2 and W3. The total thickness of the walls is 24 cm, and their schematic representations are shown in Figure 4. The core of each wall assembly is a composition of the same wall samples. The variation of thermal conductivity of all wall assemblies versus DF and TL is calculated by using previous equations, and results are given in Figure 13 and Figure 14, respectively. From those figures, huge reductions in DF values are observed for the wall assembly W2 and W3 with respect to the W1 since DF strictly depends on the thermal conductivity of wall samples. Even though the core layer has a higher thermal conductivity, the insulation layer diminishes heat fluxes through the wall because of its very low conductivity. Hence, the variations between thermal conductivity and DF for W2 and W3 assemblies are rather weak than W1.



**Figure 13.** Variation of the decrement factor versus the thermal conductivity for different wall configurations



**Figure 14.** Variation of the time lag versus the thermal conductivity for different wall configurations

The TL depends primarily on the total thickness of a wall or roof and effective thermal conductivity coefficients of the principal wall materials [37]. On the contrary, TL value does not depend, but DF depends appreciably on the location of the layers having different thermal properties. The results show that the maximum value of TL and the minimum value of DF are obtained for the wall with outer insulation (W3). It can also be revealed that the variations of thermal conductivity versus TL and DF have a similar trend for all wall configurations (W1, W2, and W3).

#### 4. CONCLUSIONS

The results can be drawn from the experimental and theoretical analyzes:

1. The results show that the approaches presented in the literature are not realistic in a significant number of cases. In the literature, the authors ignored the relationships between the thermophysical properties to calculate TL and DF.
2. Thermophysical properties of an element such as density, thermal conductivity, and diffusivity are very effective in terms of heat transfer of a building wherein each property alone (keeping the other properties constant) is not adequate to identify the thermal inertia and thermal performance of a wall element.
3. The results reveal that the degree of the relationship between TL, DF, and heat capacity is weaker than between properties such as thermal conductivity and density. Therefore, heat capacity is not a useful indicator to identify the thermal performance of a wall element.
4. Thanks to their insulation layers, huge reductions in DF values are observed for the wall assemblies of W2 and W3 with respect to the W1; hence, the effect of thermal conductivity on DF is rather weak for each of different wall assemblies. Besides, the TL depends primarily on the thickness of a wall or roof and the effective thermal conductivity of the principal wall materials.

#### CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

#### NOMENCLATURE

|          |   |
|----------|---|
| a        | thermal diffusivity ( $\text{m}^2/\text{s}$ )   |
| c        | specific heat ( $\text{kJ}/\text{kg K}$ )   |
| $h_i$    | coefficient of heat transfer at the interior surface ( $\text{W}/\text{m}^2 \text{K}$ ) |
| $h_o$    | coefficient of heat transfer at the exterior surface ( $\text{W}/\text{m}^2 \text{K}$ ) |
| $i, j$   | complex arguments   |
| $I_T$    | solar radiation incident on tilted surface ( $\text{W}/\text{m}^2$ )                    |
| $I_{bT}$ | beam radiation incident on tilted surface ( $\text{W}/\text{m}^2$ )                     |
| $I_{dT}$ | diffuse radiation incident on tilted surface ( $\text{W}/\text{m}^2$ )                  |
| $I_{rT}$ | reflected radiation incident on horizontal surface ( $\text{W}/\text{m}^2$ )            |
| L        | thickness (m)   |

|       |  |
|-------|--|
| p     | time period (h)                                |
| t     | time (s)                                       |
| $T_a$ | ambient air temperature ( $^{\circ}\text{C}$ ) |
| $T_e$ | sol-air temperature ( $^{\circ}\text{C}$ )     |
| $T_r$ | room temperature ( $^{\circ}\text{C}$ )        |

### Greek symbols

|                           |   |
|---------------------------|---|
| $\alpha_s$                | absorptance of surface  |
| $\rho$                    | density ( $\text{kg}/\text{m}^3$ )  |
| $\omega_j$                | complex frequency   |
| $\delta$                  | declination   |
| $\varepsilon$             | emissivity of a surface   |
| $\Delta R$                | difference between long-wave radiation incident on the surface from the sky ( $\text{W}/\text{m}^2$ ) |
| $\tau, \tau_n, \tau_{np}$ | dimensionless time terms  |
| $\rho_g$                  | ground reflectance  |
| $\omega$                  | hour angle  |
| $\phi$                    | latitude angle  |
| $\gamma$                  | surface azimuth angle   |
| $\lambda$                 | thermal conductivity ( $\text{W}/\text{m K}$ )  |

### Subscripts

|   |                          |
|---|--------------------------|
| i | inside                   |
| n | number of layers         |
| N | number of the last layer |
| o | outside                  |

### REFERENCES

- [1] Moosavi, L., Mahyuddin, N., Ghafar, N.A., Ismail, M.A., "Thermal performance of atria: An overview of natural ventilation effective designs", *Renewable & Sustainable Energy Reviews*, 34: 654–670, (2014).
- [2] Sun, C., Shu, S., Ding, G., Zhang, X., Hu, X., "Investigation of time lags and decrement factors for different building outside temperatures", *Energy and Buildings*, 61: 1–7, (2013).
- [3] Mazzeo, D., Oliveti, G., Arcuri, N., "Influence of internal and external boundary conditions on the decrement factor and time lag heat flux of building walls in steady periodic regime", *Applied Energy*, 164: 509–531, (2016).
- [4] Gasparella, A., Pernigotto, G., Baratieri, M., Baggio, P., "Thermal dynamic transfer properties of the opaque envelope: Analytical and numerical tools for the assessment of the response to summer outdoor conditions", *Energy and Buildings*, 43: 2509–2517, (2011).
- [5] Ruivo, C. R., Ferreira, P. M., Vaz, D. C., "On the error of calculation of heat gains through walls by methods using constant decrement factor and time lag values", *Energy and Buildings*, 60: 252–261, (2013).
- [6] Mavromatidis, L. E., Mankibi, M. E., Michel, P., Santamouris, M., "Numerical estimation of time lags and decrement factors for wall complexes including Multilayer Thermal Insulation, in two different climatic zones", *Applied Energy*, 92: 480–491, (2012).
- [7] Vijayalakshmi, M. M., Natarajan, E., Shanmugasundaram, V., "Thermal behaviour of building wall elements", *Journal of Applied Sciences*, 15: 3128–3133, (2006).

- [8] Kaşka, Ö., Yumrutaş, R., Arpa, O., “Theoretical and experimental investigation of total equivalent temperature difference (TETD) values for building walls and flat roofs in Turkey”, *Applied Energy*, 86: 737–747, (2009).
- [9] Stephan, E., Cantin, R., Caucheteux, A., Tasca-Guernouti, S., Michel, P., “Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings”, *Building and Environment*, 80: 241–248, (2014).
- [10] Ulgen, K., “Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor”, *Energy and Buildings*, 34: 273–278, (2002).
- [11] Asan, H.,” Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view”, *Energy and Buildings*, 32: 197–203, (2000).
- [12] Asan, H., “Effects of Wall's insulation thickness and position on time lag and decrement factor”, *Energy and Buildings*, 28: 299-305, (1998).
- [13] Ozel, M., “Effect of insulation location on dynamic heat-transfer characteristics of building external walls and optimization of insulation thickness”, *Energy and Buildings*, 72: 288–295, (2014).
- [14] Asan, H., “Numerical computation of time lags and decrement factors for different building materials”, *Building and Environment*, 41: 615–620, (2006).
- [15] Asan, H., Y.S. Sancaktar,” Effects of Wall's thermophysical properties on time lag and decrement factor”, *Energy Build*, 28: 159–166, (1998).
- [16] Zhang, Y., Lin, K., Zhang, Q., Di, H., “Ideal thermophysical properties for free-cooling (or heating) buildings with constant thermal physical property material”, *Energy and Buildings*, 38: 1164–1170, (2006).
- [17] Kontoleon, K.J., Theodosiou, Th.G., Tsikaloudaki, K.G., “The influence of concrete density and conductivity on walls' thermal inertia parameters under a variety of masonry and insulation placements”, *Applied Energy*, 112: 325–337, (2013).
- [18] Yunsheng, X., Chung, D.D.L., “Effect of sand addition on the specific heat and thermal conductivity of cement”, *Cement and Concrete Research*, 30: 59–61, (2000).
- [19] Khan, M.I., “ Factors affecting the thermal properties of concrete and applicability of its prediction models”, *Building and Environment*, 37: 607–614, (2002).
- [20] Oktay, H., Yumrutas, R., Akpolat, A., “Mechanical and thermophysical properties of lightweight aggregate concretes”, *Constr. Build. Mater.*, 96: 217–25, (2015).
- [21] Unal, O., Uygunoglu, T., Yildiz, A., “Investigation of properties of low-strength lightweight concrete for thermal insulation”, *Building and Environment*, 42: 584–590, (2007).
- [22] H. Canakci, R. Demirboga, B. Karakoc, O. Sirin, Thermal conductivity of limestone from Gaziantep (Turkey), *Building and Environment*, 42: 1777–1782, (2007).
- [23] ACI Committee 122, *Guide to Thermal Properties of Concrete and Masonry Systems*, American Concrete Institution, ISBN 9780870310850, (2002).

- [24] Jin, X., Zhang, X., Cao, Y., Wang, G., “Thermal performance evaluation of the wall using heat flux time lag and decrement factor”, *Energy and Buildings*, 47: 369–374, (2012).
- [25] Zhang, Y., Du, K., He, J., Yang, L., Li, Y., Li, S., “Impact factors analysis on the thermal performance of hollow block wall”, *Energy and Buildings*, 75: 330–341, (2014).
- [26] Yumrutas, R., Unsal, M., Kanoglu, M., “Periodic solution of transient heat flow through multilayer walls and flat roofs by complex finite Fourier transform technique”, *Building and Environment*, 40: 1117–25, (2005).
- [27] ASHRAE, *ASHRAE handbook-fundamentals*, ASHRAE, Atlanta, (1993).
- [28] Duffie, J.A., Beckman, W.A., *Solar engineering of thermal process*, fourth ed., Wiley, New York, (2013).
- [29] Mackey, C., Wright, L., “Periodic heat flow-homogeneous walls or roofs, *ASHVE Transactions*”, 50: 293–312, (1944).
- [30] Mackey, C., Wright, L., “Periodic heat flow-composite walls or roofs, *ASHVE Transactions*”, 52: 283–296, (1946).
- [31] Luo, C., Moghtaderi, B., Sugo, H., Page, A., “Time lags and decrement factors under air-conditioned and free-floating conditions for multi-layer materials”, 10th Conference of the International Building Performance Simulation Association, Beijing, 95-100, (2007).
- [32] Fidan, S., Oktay, H., Polat, S., Ozturk, S., “An Artificial Neural Network Model to Predict the Thermal Properties of Concrete Using Different Neurons and Activation Functions”, *Advances in Materials Science and Engineering*, vol. (2019). <https://doi.org/10.1155/2019/3831813>.
- [33] TS EN 12667 Turkish Standards Institute, *Thermal performance of building materials and products*, (2003).
- [34] ASM International Materials Properties Database Committee, *Thermal Properties of Metals*, ISBN 0-87170-768-3, (2002).
- [35] Gagliano, A., Patania, F., Nocera, F., Signorello, C., “Assessment of the dynamic thermal performance of massive buildings”, *Energy and Buildings*, 72: 361–370, (2014).
- [36] Barrios, G., Huelsz, G., Rechtman, R., Rojas, J., “Wall/roof thermal performance differences between air-conditioned and non air-conditioned rooms”, *Energy and Buildings*, 43: 219–223, (2011).
- [37] Kossecka, E., “Correlations between structure dependent and dynamic thermal characteristics of building walls”, *Journal of Building Physics*, 22: 315–333, (1999).