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AN INVESTIGATION OF THE INFLUENCE OF THERMOPHYSICAL PROPERTIES OF MULTILAYER WALLS AND ROOFS ON THE DYNAMIC THERMAL CHARACTERISTICS

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Abstract

The growing concern about energy consumption of heating and cooling of buildings has led to a demand for improved thermal performances of building materials. To achieve this goal, in this study, an investigation is performed to analyze the influence of thermophysical properties and thickness of various multilayer building walls or roofs in a building on the dynamic thermal characteristics, such as the decrement factor (DF), time lag (TL) and heat gain. In order to find the thermal performance characteristics of building structures, such as briquette, brick, blockbims and autoclaved aerated concrete (AAC), which are commonly used in Turkey, an analytical solution method was developed in a computer program in MATLAB and results are compared to determine suitable wall or roof material. Calculation method for the heat flow is based on solution of transient heat transfer problem for the multilayer structures. The program is executed to calculate hourly heat gain values for these samples over a period of 24 h during design day for Gaziantep, Turkey. It was found that thermophysical properties of roofs or walls have a very profound effect on the time lag (TL), decrement factor (DF) and also heat gain.
Keywords: Building walls, roofs, thermophysical characteristics, heat gain, time lag, decrement factor

ÇOK KATMANLI DUVAR VE ÇATI TİPLERİNİN ISIL VE FİZİKSEL ÖZELLİKLERİNİN DİNAMİK ISIL KARAKTERLERİNE OLAN ETKİSİNİN İNCELENMESİ

Özet

Binaların ısıtılması ve soğutulması için tüketilen enerjinin büyümesiyle birlikte artan endişe, ısıl performansı yüksek olan inşaat malzemelerinin ihtiyaç duyulmasına yol açmıştır. Bu amaca yönelik olarak, bu çalışmada; binalarda kullanılan çok katmanlı olan çeşitli duvar ve çatı tiplerinin kalınlık ve ısıl özelliklerinin, eksiltme faktörü, zaman gecikmesi ve ısı kazanımları gibi dinamik ısıl karakterlerine olan etkisini incelemek için bir araştırma yapılmıştır. Türkiye' de yaygın olarak kullanılan tuğla, blokbims, gaz beton gibi bina yapılarının ısıl performans özelliklerini bulmak amacıyla MATLAB tabanlı bir bilgisayar programında kullanılan, analitik bir yöntem geliştirilmiş ve sonuçlar en uygun duvar ve çatı malzemesini belirlemek için karşılaştırılmıştır. Isı geçişi değerleri çok katmanlı yapılarda geçici rejim ısı transferi probleminin çözümü kullanılarak yapılmıştır. Isı kazancını hesaplamak için, bilgisayar programı Gaziantep'te tasarım günü için 24 saat boyunca üretilen beton numuneleri için çalıştırılmıştır. Malzemelerin termofiziksel özelliklerin sönüm oranı (DF), faz kayması (TL) ve ısı kazanımlarının üzerinde çok büyük bir etkisi olduğu çalışmanın sonucunda görülmüştür.
Anahtar Kelimeler: Bina duvarları, çatıları, termofiziksel özellikler, ısı kazanımı, sönüm oranı, faz kayması.

1 Introduction

Air conditioning is one of the important things for the humanity who can live in spaces having comfort conditions along whole year. The comfort conditions may be given as dry and wet bulb temperatures, humidity, air velocity and cleaning. The temperature of the living environment which is the one of the most important comfort conditions varies with the surrounding the structure of walls and ceilings as a result of interaction with external atmospheric conditions such as wind speed, solar radiation and the ambient temperature [1].

It is possible to keep the changing temperature in the comfort zones by heating and cooling air within a space. For this reason, it is necessary to heat the living spaces in winter season by giving sufficient amount of moisture, and to cool the spaces in summer season. That is, heating ventilating and air conditioning (HVAC) system has been the most important solution for a more comfortable life. The main purpose of the HVAC system is to maintain comfortable conditions that provide thermal comfort for building occupants and conditions that are required by the products and processes within the space. Because capacities of the HVAC systems depend on the types of the walls and roofs used, and calculations of heat gain in the summer season and heat loss in the winter season accurately.

The heat gain is made up of components from many sources. The components that contribute to space cooling load consist of the followings: conduction through exterior walls, roof, and window; heat from infiltration of outside air through openings; heat gain from people, lightening and other equipment. In many buildings the heat gain through the external opaque walls and roofs constitutes a major portion of the total cooling load of a space. From the point of view, types of the walls and roofs to be used in building constructions and calculation of the heating and cooling load due to heat loss and heat gain from these structures are very significant. Based on the concept of transfer functions, basic methods have been developed over the years for estimating cooling loads on the buildings [6]. These are transfer function method (TFM), cooling load temperature difference (CLTD) method and total equivalent temperature difference (TETD) method, and radiant time series (RTS) method. The TFM introduced by ASHRAE [2] is considered to be one of the most accurate methods for calculating heating and cooling loads; and it uses a set of construction types with recalculated conduction transfer functions coefficients These coefficients are tabulated for certain types of walls, partitions, roofs, floors, and ceilings in ASHRAE by utilizing the TETD and CLTD method [2]. It is limited by the tabulated data for the particular walls and roofs used in North America with certain inside and outside conditions. It would be desirable to develop analytical methods which do not require the use of tables and be applicable for any possible construction and outdoor thermal conditions [3]. Yumrutaş et al. [4], [5] developed a theoretical methodology based on periodic solution of one-dimensional transient heat transfer problem for the building structures in order to estimate heat gain values through walls and flat roofs with N layers.

The estimation of the dynamic thermal behavior of building structures has recently become focus of great interest. Several relevant studies of characteristics of building structures have been conducted. Dilmaç and Eğrican [6] investigated the influence of the thermophysical properties of different wall types on the dynamic thermal characteristics such as, heat storage, time lag, and decrement factor in order to provide thermal comfort and compare the heat gain through these structures. Eğrican and Onbaşıoğlu [7] investigated the thicknesses of four different wall materials to provide maximum heat storage capacity of a homogenous wall structure. In their studies, the heat wave that represents the sol–air temperature is assumed to show a sinusoidal variation. Asan and Sancaktar [8], and Asan [9] investigated time lag and decrement factor by employing the Crank- Nicolson scheme. He obtained that insulation thickness, types of building materials and their positions have a very profound effect on time lag and decrement factor. In another study, Ulgen [10] examined experimentally and analytically the thermal response of various wall formations under the effect of solar radiation.

In this study, formulation of the transient heat transfer problem for the multilayer structures is defined by a differential equation, initial and boundary conditions. Then, the formulation is put in dimensionless form using dimensionless variables, and the problem is solved by applying Complex Finite Fourier Transform (CFFT) to the dimensionless formulation. As a result of the solution, the values of heat gain, time lag and decrement factor are obtained as a function of surface temperatures for eight different walls and two different flat roofs commonly used in Turkey. The results obtained from the theoretical study are explained and discussed in detail.

2 Formulation of Mathematical Model

Heat transfer through a building wall is functions of indoor and outdoor temperatures, temperatures of the surrounding and interior surfaces, heat transfer coefficients at the inner and outer surfaces, and solar radiation input on the outer surface of the wall. If the inner surface temperature of the wall can be obtained, heat transfer to the room maybe calculated using this surface temperature, combined heat transfer coefficient at the surface, and the indoor temperature. In this section, analytical model will be presented for finding the values of inner surface temperature and also heat gain from the building exterior wall. The first section contains solution of periodic transient heat transfer problem for multilayered wall. Hourly temperature distributions in the wall will be estimated by using the solution. The second is for calculation of solar radiation flux on any wall surfaces using hourly solar radiation flux on horizontal surface. The calculated solar radiation flux is used to obtain sol-air temperature for the wall. Calculation of TL, DF and heat gain values from the exterior walls is presented at the last section.

2.1 Solution of Transient Heat Transfer Problem

Temperature variations at the inside and outside surfaces of building exterior walls are required to find heat flux for the walls. Therefore, analytical solution procedure for periodic transient temperature field problem for the walls is presented in this section. The walls are composite structures which consist of n layers with thicknesses of Ln. Each layer has homogenous structure with constant thermal properties. The following assumptions are considered.

a) There is a good contact between the layers; hence the interface resistance is negligible.

b) There is no heat generation in each layer of walls.

c) The variation of thermal properties is negligible.

d) The convection coefficients are constants and are based on the direction of heat flow.

Under these assumptions, the transient heat flow through the building exterior walls can be expressed as functions of the inner surface temperature and overall heat transfer coefficient. Therefore, it is necessary to find the inside and outside surface temperature of the exterior walls. The temperatures can be found by solving transient heat transfer problem for the composite walls. The transient periodic heat transfer problem can be defined as partial differential equation, boundary and periodic conditions, and presented in this paper.

$$\frac{\partial^2 T_n}{\partial x_n^2}=\frac{1}{\alpha_n}\frac{\partial T_n}{\partial t} \qquad 1\le n \le N \qquad (1)$$

$$h_i(T_r-T_1)=-k_1\frac{\partial T_1}{\partial x_1} \qquad at\ x_1 = 0 \qquad (2)$$

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

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

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

$$T_a(t)+\frac{\alpha_s I_t(t)}{h_o}-\frac{\varepsilon\Delta R}{h_o} \qquad at\ x_N = L_N \qquad (6)$$

in Eq. (6) , T_e and T_a are the sol-air and ambient temperatures; respectively, I_T is the solar radiation flux. For horizontal surfaces that receive long-wave radiation from the sky only, the appropriate value of ΔR is about 63 W/m^2, also it is common practice to assume "$\Delta R = 0$" for vertical surfaces.

The problem formulation consisting of Eqs. (1)-(6) is converted into dimensionless form by introducing dimensionless variables and periodicity condition $T_n(x_n, t) = T_n(x_n, t+p)$. Its expression and calculation procedure are presented in Yumrutaş et al. in detail [1], [3]. The following Complex Finite Fourier Transform (CFFT) is applied to the dimensionless formulation of the problem. Finally, the general closed solution of the problem for finding hourly heat gain through the wall and flat roof is,

$$q = h_i\left[T_n(0,\tau) - T_r\right] \qquad at\ z_n=0 \qquad (7)$$

then obtained.

2.2 Hourly Solar Radiation Flux on Exterior Wall Surface

The value of heat gain through the wall depends on sol-air temperature which is a function of solar radiation flux I_T presented in Eq. (6). The I_T is hourly total solar radiation incident on the wall surfaces. It is computed using hourly measured solar radiation on a horizontal surface which were taken from the local meteorological stations located in Gaziantep. The total solar radiation on any wall surface consists of three components which are beam radiation I_{bT}, diffuse radiation I_{dT} and reflected radiation I_{rT}.

$$I_T(t) = I_{bT}(t) + I_{dT}(t) + I_{rT}(t) \qquad (8)$$

the hourly total solar radiation on the wall surface is given in Duffie and Beckman [11].

$$I_T(t) = I_b(t)R_b + I_d(t)\frac{1+\cos\beta}{2} + \rho_g I(t)\frac{1-\cos\beta}{2} \qquad (9)$$

where ρ_g is ground reflectance, and is usually taken as 0.2. Parameter R_b is the ratio of beam radiation on tilted surfaces to vertical surfaces and given as:

$$R_b = \frac{\cos\delta\sin\phi\cos\gamma\cos\omega + \cos\delta\sin\gamma\sin\omega - \sin\delta\cos\phi\cos\gamma}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \qquad (10)$$

2.3 Calculation of Time Lag (TL) and Decrement Factor (DF)

The time lag shown as TL is defined as the time required for a heat wave to propagate through a wall or flat roof from the outer to the inner surface. On the other hand, the decrement factor shown as DF is defined as the decreasing ratio of its temperature amplitude during the transient process of a wave penetrating through a solid element. The schematic representations of the TL and DF are shown in Figure 1. The TL and DF are very important characteristics of a building wall and roof structures to determine their heat storage capabilities. In this study, the TL and DF are computed by the following relations:

$$\delta_s = t_{T_{i,\max}} - t_{T_{e,\max}} \qquad (11)$$

$$\lambda = \frac{A_i}{A_e} = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \qquad (12)$$

In Eqs. (11) and (12); $t_{Te,max}$, $t_{Ti,max}$ express the times when interior surface and sol-air temperatures are at their maximums, respectively. Also, $T_{i,max}$, $T_{i,min}$, $T_{e,max}$ and $T_{e,min}$ are the minimum and maximum interior surface and sol-air temperatures, respectively.

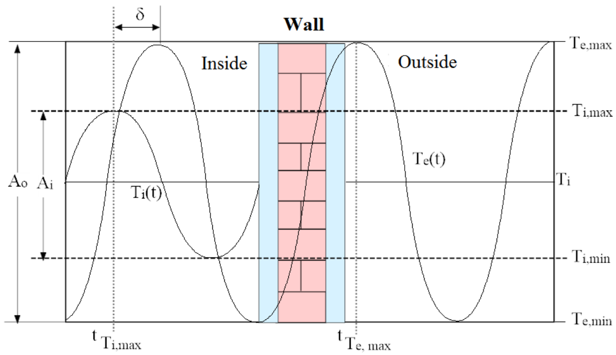

Figure 1. Schematic representation of time lag (TL) and decrement factor (DF).

3 Computational Procedure

A computer program is prepared in MATLAB in order to carry out the numerical calculations of TL, DF and heat gain values. Some parameters are used as input parameters in this program. These parameters are hourly solar radiation flux on horizontal surface measured by meteorological stations, thermal and physical properties such as number and thickness of layers, density, specific heat, thermal conductivity and diffusivity, combined convection heat transfer coefficient for both sides of inside and outside air, hourly outside air temperature and inside design air temperature. All of these input parameters used in program are presented below in detail.

3.1 Thermophysical Characteristics of the Wall Materials

The eight walls and two roofs are commonly used wall and roof types in Turkey. The walls are selected as briquette, brick, blokbims, Autoclaved Aerated Concrete (it will be called as AAC in this study), XPS, EPS, covering and siding walls. Schematic representation of the walls and roofs are given in detail in Figure 2. Roof 1 is composed of 12 cm concrete and 2 cm plaster, and there is 5 cm XPS as an insulation material placed between the concrete and the plaster for Roof 2. In order to compute the values, it is necessary to know the thermal and physical properties which are thicknesses, conduction heat transfer coefficient, density and specific heat of the wall materials. Thermal and physical properties of the wall materials used in this study are listed in Table 1.

Besides, absorptivity of a building wall is another important parameter. Because absorbed solar energy depends on the absorptivity constant. Each color has an absorptivity constant; in this study, black, green, brown and white colored walls are used. Their absorptivities are taken as 0.85, 0.80, 0.75 and 0.48, respectively [2], [12].

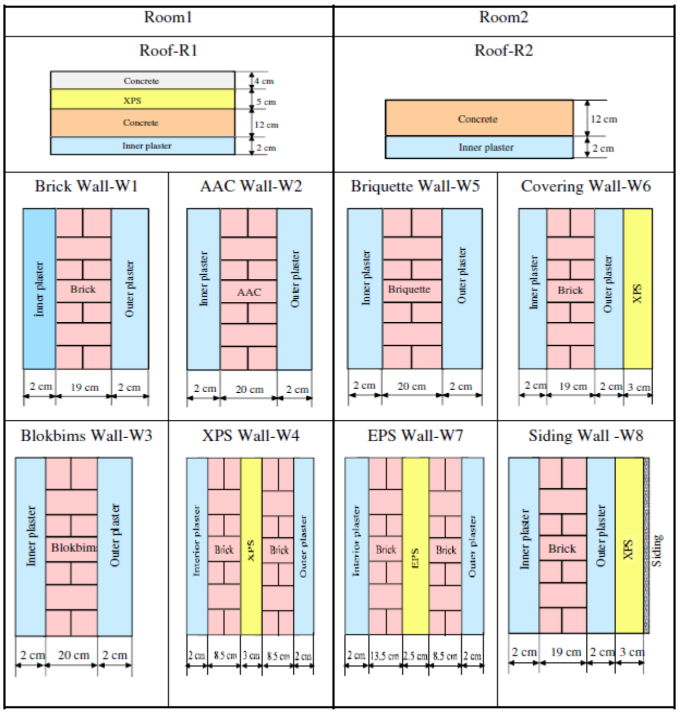

Figure 2. Configuration of the roofs and walls used in the study.

3.2 Climatic Data

The temperature variations and heat gain are functions of climatic conditions. The climatic data are two of the most important factors. Therefore, it is necessary to know the design conditions and climatic data. The inside air temperature is taken to be 25 °C. Combined heat transfer coefficients at the inner and outer surfaces are taken to be 9 and 17 W/m²°C, respectively. In order to calculate the hourly solar radiation flux on any wall surface and hourly outside air temperatures, 10 years long term measured data were taken from the local meteorological stations for 23 July located in Gaziantep.

Table 1. Thermophysical properties of building materials

Wall types	Thermal conductivity k (W/m K)	Density ρ (kg/m^3)	Specific heat c (kJ/kg K)	Heat capacity ρc (kJ/m^3 K)	Thermal diffusivity α (m^2/s)
Briquette	0.920	1600	0.840	1344.00	6.84×10^{-7}
Brick	0.690	1580	0.840	1327.20	5.20×10^{-7}
Blockbims	0.230	770	0.835	642.95	3.57×10^{-7}
AAC	0.150	400	1.047	418.80	3.58×10^{-7}
Concrete	1.370	2076	0.880	1826.88	7.50×10^{-7}
Plaster	0.700	2778	0.840	2333.52	2.99×10^{-7}
XPS	0.034	22	1.280	281.60	12.1×10^{-7}
EPS	0.038	18	1.500	27.00	14.0×10^{-7}
Siding	0.094	640	1.170	748.80	1.26×10^{-7}

4 Results and Discussions

In this study, the values of heat gain, TL and DF for eight types of walls, and for two types of roofs with and without insulation material are determined utilizing measured values and are shown using figures. In order to investigate the effect of wall direction and color on heat gain, the brick wall are selected and daily variation of heat gain values through the walls are presented. Solar insolation on hourly basis incident on the walls and roof are calculated using the method in Duffie and Backman [11] by inserting data for hourly ambient air and sol-air temperatures and shown in Figure 3. The sol–air temperatures reach the highest values for the horizontal surface, and sol–air temperatures for the west wall are higher than those for the east. When solar radiation is high, solar-air temperature is also high. In this case, the directions of walls have important concern in construction of a building in terms of cooling load.

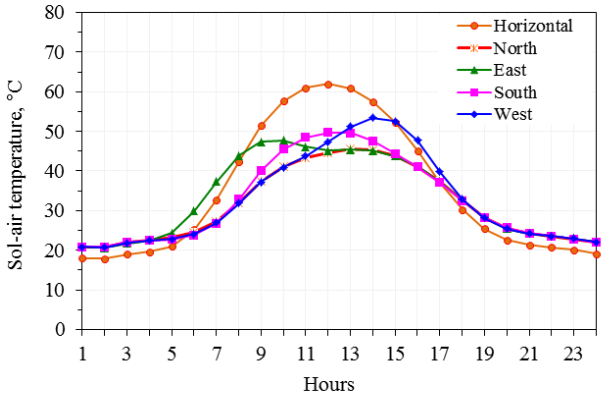

Figure 3. Variation of sol-air temperatures for four main vertical surfaces.

Figs. 4 shows the daily variation of heat gain values of dark colored brick wall (W1). As seen in Figure4, the highest amplitude of heat gain is obtained for the West direction and the lowest one is obtained for North direction. The higher values of outside air temperatures and solar radiation during afternoon hours yield higher values of sol air temperatures. It is necessary to calculate the cooling load due to heat gain for the West direction, and to minimize wall surface area directed due to West when a building will be constructed.

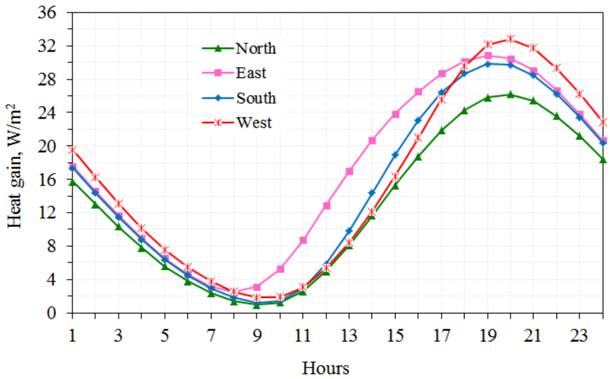

Figure 4. Daily variation of heat gain values of dark colored brick wall (W1).

Another effect of any wall or roof surface on heat gain is surface color. The surface color of any exterior surface is very important for heat gain values of any wall or roof, since heat gain of any space from exterior walls depends on heat flux absorbed by the wall surface. In order to see the effect of surface color on heat gain, Figure 5 is depicted for white, brown, green and black colored brick walls with thicknesses of 20 cm and directed to south. As shown in Figure5, the highest heat gain is obtained for the black colored and the lowest one is obtained for the white colored walls. This indicates that colors of building exterior surfaces are very important. Especially, any building should be constructed with light colors for the places near to the equator or having high solar flux to decrease cooling load and load on the cooling system in order to reduce the operational cost.

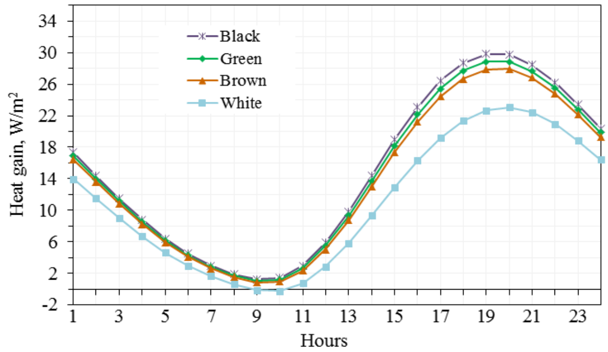

Figure 5. Effects of surface colors on heat gain values for brick wall (W1) due to south direction.

Figure 6 is depicted for comparing heat gain values of the light and dark colored roofs with and without XPS (insulation material) which are named as R1 and R2, respectively. Absorptivity of surfaces and thermophysical properties has profound effect on the heat gain values. The difference between hourly heat gain values of light and dark roof is about 4 W/m2. Since the roof R1 has high thermal resistance, there are low oscillations of the heat gain. R2 gives high oscillations for the daily heat gain values because its thermal resistance is considerably low. Hence, amplitude of the heat gain values for R2 is fairly higher than the amplitude of the R1 which is about 11 times. The amplitude of daily heat gain values is the functions of both the TL and DF but the DF is dominant for the amplitude in heat gain. The TL for the R1 and R2 are equal to 7.05 and 4.05 h, and the DF's for the same roofs are obtained as 0.0206 and 0.2940, respectively. The heat gain values of R2 reach the lowest and the highest values between the hours of 5 - 7 and 15 -17, respectively. The lowest and highest heat gain values for R1 occur at about the hour of 9 and 19, respectively. The shifts in hours are indication of effects of thermal resistance for the roofs R1 and R2. High heat gain values of the R2 indicate high level of heat gain and uncomfortable conditions. The R2 roof is commonly used in houses with one floor in Turkey, and it is a thermally poor construction.

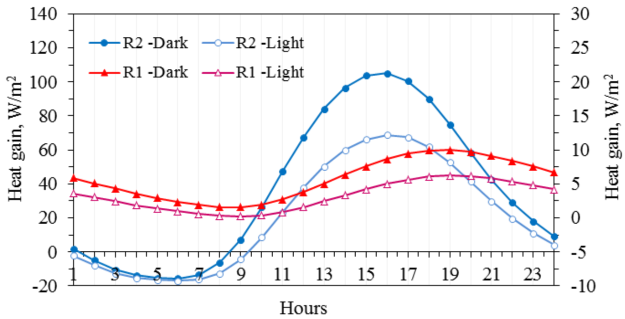

Figure 6. Comparing heat gain values of the light and dark colored roofs with (R1) and without XPS (R2).

Daily variations of heat gain values of the walls used in the test rooms are shown in Figure 7. Briquette wall has the highest amplitude of the heat gain value and this is followed by brick, blokbims, AAC, XPS, EPS, covering and siding and the heat gain values are 34.335, 29.818, 13.834,11.824, 10.26, 9.663, 7.308 ve 6.286 W/m2 , respectively. As seen here, the heat gain value of siding wall is aproximately a fifth of briquette wall's. Capacity of the selected air conditioning system increases when the cooling load increases in terms of heat gain. As the capacity increases energy requirement and operation cost of the system will increase. It is desirable to use the minimum capacity provided that comfort conditions are satisfied. The heat gain values or the amplitudes for the blokbims wall are close to those of AAC. This indicates that the thermophysical properties of the blokbims and AAC are also close to each other. The blokbims are produced from natural volcanic materials, which are located at Kayseri and Nevşehir regions at the middle Anatolian region of Turkey. It is considered that formation of blokbims material is similar to the industrial production of the AAC. The cost of blokbims is lower than AAC because of natural existence of its material in Turkey.

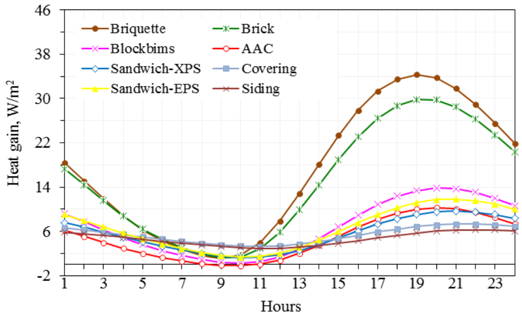

Figure 7. Daily variation of heat gain values of dark colored walls due to south direction.

The order from the highest to the lowest DF and the lowest to the highest TL values in Figure 8 is presented for briquette, brick, XPS, EPS, blokbims, AAC, covering and siding walls, respectively. Sequence of the walls based on heat gain values depends on thermophysical properties of the wall and roof materials. The properties of the materials, such as conductivity, density, specific heat, heat capacitance and thermal diffusivity are very important, which are measure of transient heat flow. These properties are given in Table 1. In thermal behavior, heat capacitance, which is the ability of a material to absorb and store heat for later use, is the more effective parameter. Thermophysical properties of wall materials have very profound effect on the time lag and decrement factor which effect heat gain values. Because the higher heat capacitance gives the higher heat gain. The DF values for briquette, brick, XPS, EPS, blockbims, AAC, covering and siding walls are calculated 0.1226, 0.1061, 0.0503, 0.0388, 0.0386, 0.0310, 0.0150 and 0.0124, and TL values are followed as 6.94, 7.30, 8.14, 8.63, 7.90, 8.75, 9.34 and 9.83 hours, respectively. When the comparison is made between the siding and brick wall, it can be observed as the 10 times difference between these walls in terms of values of DF. This situation shows that the thermal insulation is very important factor to achieving thermal comfort for a building. When the external surface color in a building is investigated, light colors increase the TL but decrease the DF values. In addition to the thermophysical properties of building structures, the surface color in terms of absorptivity has profound effect on the thermal comfort in a building.

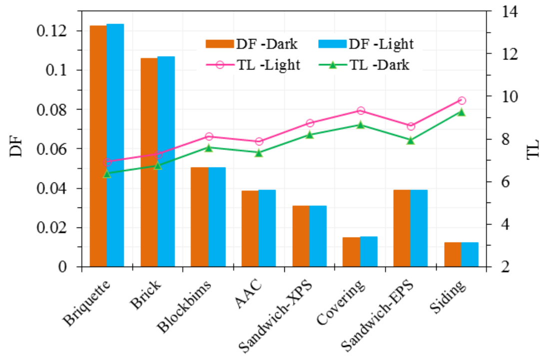

Figure 8. Daily variation of TLand DF values of dark and light colored walls due to south direction.

Figure 9 shows the effect of the thermal conductivity values, which is an important thermopysical property on TL and DF. It is observed from the Figure 9 that there is a direct relation between the DF and thermal conductivity values of selected walls. It is hardly difficult to establish a direct relation between TL and thermal conductivity as shown in thermal conductiviy and DF. Besides, the increase of the thermal conductivity values decrease TL of selected walls conducted as Asan ve Sancaktar [7], a different situation arises as shown in Figure 9. The TL and thermal conductivity values of dark colored blockbims and AAC walls are 8.14, 7.90 hours and 0.230 ve 0.150 W/mK, respectively. The increase of the thermal conductivity values does'nt directly decrease the TL value as thought before. Furthermore, when a comparison is made between heat capacity values, which is another important thermopysical property, The heat capacity value of blockbims (642.95 kJ/m³K), is higher than that of AAC (418.80 kJ/m³K). Despite the fact that the thermal conductivity value of Blockbims is higher than AAC, the higher heat capacity value of blockbims has prevented the lower TL. This will be discussed in more detail in a further study.

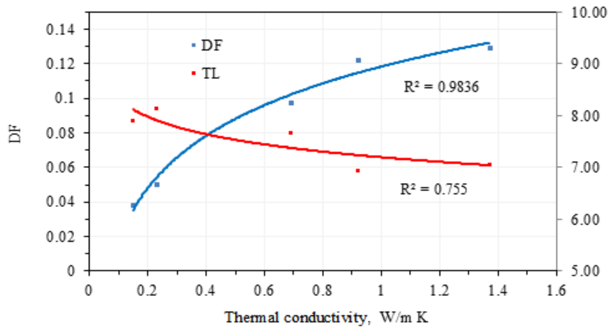

Figure 9. The effect of the thermal conductivity values on TL and DF for dark colored walls.

5 Conclusion

The time lag (TL), decrement factor (DF) and heat gain values of eight types of walls and two types of flat roofs commonly used in Turkey are obtained using theoretical studies. Some of the conclusions can be summarized as follows:

1. Meteorological values, absorptivity of surfaces, thermophysical properties and directions of the walls have significant effects on the the TL, DF and heat gain values.
2. Briquette wall has the highest amplitude of the heat gain value, covering and siding wall have the highest

amplitude of the heat gain value through the selected walls. it will be a very useful guide for practitioners when an analysis (both energy and economic) is performed considering the heat losses and gains of these walls in heating and cooling season.

3. Both increase in TL and decrease in DF give lower heat gain values.
4. The highest values of TL and DF are obtained as 9.83 h and 0.1226 for siding and briquette, respectively. Besides, the lowest values of TL and DF are obtained as 6.94 h and 0.0124 for briquette and siding; respectively, from the selected walls. This situation shows that the thermal insulation is very important factor to achieving thermal comfort for a building.
5. The heat gain values obtained for the blockbims, which are produced from natural volcanic materials, which are located at Kayseri and Nevşehir are close to the values of AAC.
6. It can be concluded that there is a direct relation between the DF and thermal conductivity values of selected walls; however, It is hardly difficult to establish a direct relation between TL and thermal conductivity as shown in thermal conductiviy and DF.

6 References

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Nomenclature

h_i	combined heat transfer coefficient at the inner surface [W/m² K]
h_o	combined heat transfer coefficient at the outer surface [W/m² K]
I_T	radiation heat flux on tilted surface [W/m²]
I_{bT}	beam radiation heat flux on tilted surface [W/m²]
I_{dT}	diffuse radiation heat flux on tilted surface [W/m²]
I_{rT}	reflected radiation heat flux on horizontal surface [W/m²]
k	thermal conductivity [W/m K]
L	thickness [m]
q	heat gain through the wall [W/m²]
t	time [s]
T_a	ambient air temperature [°C]
T_e	sol-air temperature [°C]
T_r	design inside air temperature [°C]

Greek symbols

α	thermal diffusivity [m²/s]
α_s	absorptance of surface
ρ_g	ground reflectance
ϕ	latitude angle
ω	hour angle
γ	surface azimuth angle,
δ	declination
δ_s	time lag [hour]
λ	decrement factor
τ	dimensionless time

Subscripts

i	inside
j	number of terms
n	number of layer
N	number of last layer
o	outside