Comparison of Different Insulation Materials with Thermal Conductivity Coefficients Based on Density and Temperature for Two Climate Zones

Mehmet Kan

Received: 23 August 2022 / Accepted: 24 September 2022 / Published online: 1 October 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
The selection of insulation material and the determination of the optimal insulation thickness are very important for saving energy and ensuring thermal comfort. There are numerous studies in the literature for determining the optimum insulation thickness. In these studies, the thermal conductivity coefficient (k) of the insulation material is taken directly from the standardized tables and the optimum insulation thickness is calculated. In real applications, the k value of the insulation material varies depending on the production conditions, density and temperature. For this reason, the density of the insulation material and the operating temperature should be considered when determining the optimum insulation thickness. In this study, expanded polystyrene (EPS), extrude polystyrene (XPS), glass wool and rock wool with different densities were used as insulation materials, coal and natural gas were used as fuel. For Konya and Sivas provinces, which are in the 3rd and 4th climate zones of Turkey, a comparison was made using the degree-day method as a function of energy cost, and the insulation thicknesses were determined as a function of density and temperature. As a result of the calculations for the k value of the insulation material for Konya, which is in the 3rd climatic zone, the optimum insulation thickness was found to be 0.076 m for EPS with a density of 30 kg·m$^{-3}$, 0.037 m for XPS with a density of 30 kg·m$^{-3}$, 0.082 m for glass wool with a density of 100 kg·m$^{-3}$, 0.051 m for rock wool with a density of 150 kg·m$^{-3}$. When coal is used as fuel, the optimum insulation thicknesses for EPS, XPS, glass wool and rock wool are 0.092, 0.061, 0.104, and 0.078, respectively. As a result of the calculations for the k value of the insulation material for Sivas province, which is in the 4th climate zone, the optimum insulation thickness for EPS with density of 30 kg·m$^{-3}$ was found to be 0.086 m, for XPS with density of 30 kg·m$^{-3}$ was found to be 0.044 m, for glass wool with density of 100 kg·m$^{-3}$ was found to be 0.092 m, for rock wool with a density of 150 kg·m$^{-3}$ was found to be 0.058 m. When coal is used as fuel, the optimal insulation thicknesses for EPS, XPS, glass wool and rock wool are 0.098, 0.069, 0.106, 0.081, respectively. When comparing the insulation materials, although the
unit price of the XPS material is higher, its optimal thickness is lower than that of the other insulation materials in all situations due to its low thermal conductivity.

**Keywords** Optimum insulation thickness · Payback period · Thermal conductivity coefficient

1 **Introduction**

Energy is one of the indispensable components of social life and economic development. Depending on the technological developments, the total energy demand in the world is increasing day by day, and finally energy is becoming the most important strategic value of our time. Buildings must not only provide protection, but also create comfortable living conditions inside. Especially in winter, when indoor temperatures are higher than outdoor temperatures, thermal insulation materials play an important role as heat is transferred to the outside. The amount of heat transfer depends on the heat transfer coefficient of the building. For this purpose, it should be designed according to the heat transfer coefficient and considering the climatic conditions of the building. For this reason, the building’s construction materials should have a heat transfer coefficient suitable for the climatic region [1].

Thermal insulation is used in buildings to reduce energy losses and lower energy costs. Since concrete is a material with low thermal resistance, it is necessary to use insulation materials because heat loss in buildings is high [2]. Thermal insulation helps to reduce cooling problems by keeping out hot air in summer or cold air in winter, depending on climatic conditions. Thanks to thermal insulation, the heat flow between two different environments due to the temperature difference is reduced. In addition, the initial investment costs increase due to the use of insulation materials. However, it has been found that thanks to the energy savings obtained, considering the payback period, the energy consumption is avoided, and the energy consumption decreases in the following years [3–7]. Kaynaklı et al. [8] calculated the optimal insulation thickness for Istanbul to be 0.4 m and 0.26 m, respectively, for the case where natural gas is used in the heating season and electricity is used in the cooling season and determined an overall savings rate of 40 % for heating and 28 % for cooling. Ertürk [9] found that the optimal insulation thickness decreased from 0.092 m to 0.034 m and the total cost was reduced by 28 % when natural gas was used as fuel and XPS was used for insulation in addition to 4 mm air gap for Ankara province (Turkey). Gustafsson [10] conducted a study in Sweden on the optimization of improvement measures to minimize the life cycle costs of buildings in need of renovation. In the study, the economic dimension of the improvement was investigated by considering parameters such as the lifetime of the building, reduction of energy costs, application of insulation materials, and replacement of heating systems. Yuan et al. [11], in their study conducted in 32 different regions of China with two different walls and three different fuels, found a 63 % decrease in CO$_2$ rate under optimal conditions. Işık and Tuğan [12] determined ideal insulation thicknesses of 0.079 m, 0.082 m, and 0.1040 m for Tunceli, Hakkari, and Kars provinces.
(Turkey) with different insulation materials and variable heating degree-day values. It was also found that the ideal insulation thickness for Turkey is between 0.028 m and 0.096 m. Layberry [13], in his study in Spain, established a new degree-day data set in the range of building base temperatures from 10.5 °C to 20 °C weekly and monthly for 77 regions. By dividing the regions into four regions according to the approximate values of average insulation thicknesses, it was shown that the optimal ratio can be determined based on degree-day values. In his study, Papadopoulos [14] found that the insulation materials are composed of inorganic fibers and organic foam products of the European market, and both have similar characteristics in terms of insulation performance. In his studies, he presented the best types of insulation materials for future discussion. Christenson [15] studied the effects of climate on energy demand in Swiss buildings using the degree-day method. He developed a new method for calculating heating and cooling degree-days from monthly temperature data and tested and applied it to 4 representative Swiss sites. Yu et al. [16] compared different insulation materials in their study to determine the optimal insulation thickness for summer and winter seasons in different regions of China. Liu et al. [17] preferred EPS and XPS as insulation materials to calculate the annual energy consumption for China. As a result of the calculations, they found that the optimal insulation thickness is between 0.053 m and 0.069 m for XPS and between 0.081 m and 0.105 m for EPS. Gölcü et al. used rock wool as an insulation material in an exterior wall model. They calculated the optimal insulation thicknesses, energy savings and payback periods for this building wall [18].

In addition to reducing fuel consumption and saving energy, thermal insulation increases the life of the building by helping to improve thermal comfort and reduce condensation and mold problems by increasing the surface temperature of the walls. Generally, the average outdoor temperature, the k value of the insulation material and the cost are considered when selecting the insulation material. However, the climatic conditions that change throughout the year, the operating temperature of the insulation material, its mechanical properties, its vapor diffusion resistance, its sensitivity to chemicals, and its resistance to combustion must also be considered. However, the optimal insulation thickness depends on insulation and fuel costs, cooling and heating loads, heating system efficiency, cooling equipment performance, building life, and economic data such as interest rates and inflation. In Turkey, the “Thermal Protection Rules for Buildings” are set according to the number of degree-days (DD) according to the standard TS 825. The heat loads are calculated depending on the climatic conditions of the buildings. With an equilibrium temperature of 15 °C and an indoor temperature of 20 °C, the number of degree-days is less than 1500 for the first zone and more than 4500 for the fourth zone [19].

As can be seen from the literature, the number of heating degree-days is generally considered when determining the optimal insulation thickness. On the other hand, a constant thermal conductivity value for insulation materials has been chosen in almost all studies. Under real conditions and in practice, manufacturers produce with different density values. This leads to the fact that the thermal conductivity value of the selected insulation material and the calculated optimal insulation thickness change. For this reason, it is necessary to calculate the optimum insulation thickness as a function of the changing density value and thus the thermal conductivity value.
In this study, the thermal conductivity values (k) for EPS, XPS, glass wool and rock wool with different density values were determined using a measuring device based on the heat flux measurement (HFM) method, which was first calibrated according to the TS ISO 8302 standard. The determined k values were then used to calculate the optimum insulation thickness as a function of heating and cooling degree-days. In addition to the optimal insulation thickness, the payback periods and percentage savings were also calculated for two different fuel types, Konya province in Turkey’s 3rd climate zone and Sivas province in the 4th climate zone. These different insulation materials were compared in terms of their costs.

2 Materials and Methods

Expanded polystyrene (EPS), extruded polystyrene (XPS), glass wool and rock wool are still used intensively for insulation purposes in Turkey. The heat transfer coefficient varies depending on the density of the material, pore structure, humidity and temperature. In our country, four different climatic zones have been defined according to TS 825. The provinces are divided into regions considering the outdoor temperature, sunshine duration and humidity. Konya is in the 3rd region and Sivas in the 4th region. The proper boundary conditions set for the area where the building is located will ensure the correct determination of the optimal insulation thickness. For this study, EPS, XPS, glass wool and rock wool boards with different density values were used as insulation material. These samples were prepared with a 300 × 300 mm measuring device to determine their thermal conductivity (k). In accordance with the standard, the k value was measured on samples prepared at an average temperature of 10 ºC. The thermal conductivity coefficient was determined using the device “Heat Flow Meter, (HFM) Fox 314” (Fig. 1). The thermal conductivity coefficient was measured using the standards TS EN 12664 (2009), TS EN 12667 (2003) and ASTM C518 (2003).

A Fox-314 HFM was used to evaluate thermal conductivity in accordance with the EN 12664 and 12667 standards. Measurements started at − 10 ºC and went up
to 50 °C in 5 °C increments. The samples used in the studies had densities ranging from 8.9 kg·m\(^{-3}\) to 60 kg·m\(^{-3}\). The thermal conductivity of all closed-cell insulation materials increases with increasing temperature, as also described in the cited literature [20]. The thermal conductivity of the lower density samples increased faster with increasing temperature. In other words, low density means larger pores and much more air, resulting in higher k values. The results show that as density increases, k values decrease for the same material types, which is consistent with previous research [20]. In addition, the 3ω method is used to measure the thermal properties of building materials [21, 22]. The thermal conductivity coefficients of the samples will be used to determine the optimum insulation thickness. The k values and average unit prices measured by the HFM method are given in Table 1. Optimum insulation thicknesses were determined using these properties of the measured samples. For this purpose, an externally insulated wall structure consisting of 2 cm plaster, 20 cm thick brick and insulation material on its outer and inner surfaces is considered.

The FOX 314 Heat Flow Meter is an accurate, easy-to-use instrument for measuring thermal conductivity in accordance with ASTM C518 and ISO 8301. The FOX Heat Flow Meter operates in stand-alone or PC-controlled configurations and provides fast and accurate results. The instrument features proprietary thin-film heat flux probes, digital thickness measurements and responsive temperature control. The LaserComp heat flux transducer, designed and manufactured exclusively for thermal conductivity measurements, is the key component of the measurement. To provide accurate measurement of total heat flux, the heat flux transducer is integrated over the entire active area (100 × 100 mm). Distortion of the heat flux is not possible because the total thickness of the transducer is less than 1 mm. Each transducer is connected to a type E thermocouple in the center, and both are sealed to ensure accuracy over the life of the instrument. The thermocouples give accurate readings of the sample’s surface temperature (with a resolution of 0.01 °C) and heat flow since they are all placed within 0.1 mm of the sample’s surface. The control of plate temperature likewise employs the same thermocouples. The thermal Conductivity Range is 0.005 W·m\(^{-1}\)·K\(^{-1}\) to 0.35 W·m\(^{-1}\)·K\(^{-1}\). The uncertainty of the HFM type FOX-314 thermal conductivity measuring device is ± 3 % to 5 % and the reproducibility value is ± 0.5 %. As it can be seen from Table 1, it has been measured that the transmission coefficients of the insulation materials are quite low. It has been observed that these measurement results are in accordance with the measurement range given in the device. In addition, it has been seen in the literature that the transmission coefficients of these insulation materials overlap with each other, and their accuracy has been determined in the literature [20, 23].

Air infiltration through exterior walls, windows, ceilings, and floors is the most common source of heat gain and loss in buildings. However, in this study, only heat gains and losses from exterior walls were considered, and the ideal insulation thickness was calculated using the heat transfer coefficient, which varies with density. The heat gains and losses at the exterior wall surface are as follows [9, 23, 24].
where \( U \) is the total heat transfer coefficient \( \Delta T \), the difference between the changing outdoor temperature during the day and the constant indoor temperature. In this case, the annual heat gains and losses of the unit surface are given as a function of degree-day (DD) [9, 23, 24].

\[
q_A = 86400 \cdot DD \cdot U
\]  

(2)

The total heat transfer coefficient of the wall can be written as:

\[
U = \frac{1}{R_i + R_w + R_y + R_o},
\]  

(3)

where \( R_i \) and \( R_o \) are the thermal resistances of the interior and exterior environments, and \( R_w \) is the thermal resistance of the uninsulated wall layers. \( R_y \) is the thermal resistance of the insulating material and can be written as follows.

\[
R_y = \frac{x_y}{k_y},
\]  

(4)

where \( x_y \) is the thickness of the insulation material and \( k_y \) is its thermal conductivity. The total heat transfer coefficient, where \( R_{wt} \) is the total thermal resistance of the wall without the insulating material, is as follows [20–26].

\[
U = \frac{1}{R_{wt} + \frac{x_y}{k_y}}
\]  

(5)

The heat transfer coefficient on the inner and outer surfaces of the wall was assumed to be 7.69 W·m⁻²·K⁻¹ and 25 W·m⁻²·K⁻¹, respectively, and \( R_{wt} = 0.6 \) m²·K⁻¹·W⁻¹. Applying insulation to the external walls of the buildings significantly reduces heat gains and losses. In this case, it is necessary to know the optimal thickness of insulation in terms of energy savings. The optimal thickness of insulation is the value that causes the lowest total cost, including the cost of insulation and the cost of energy consumption during the life of the building. Therefore, the optimal insulation thickness should be determined through a cost analysis. The annual energy costs for heating and cooling are as follows:

### Table 1. Measured thermal conductivity coefficients and unit prices of insulation materials

| Material     | EPS   | XPS   | Glass wool | Rock wool |
|--------------|-------|-------|------------|-----------|
| \( \rho \) (kg·m⁻³) | 32    | 32    | 100        | 150       |
| Price [$/m³]  | 42    | 91    | 47         | 72        |
| \( k \) (W·mK⁻¹) | 0.0306| 0.026 | 0.032      | 0.033     |
where HDD and CDD stand for heating degree-days and cooling degree-days, respectively, and are given in Table 2 for Konya and Sivas.

\( C_f, C_e, H_u, \eta \) and COP are the fuel price (\$/kg), the price of electricity (\$/kWh), the lower heating value of the fuel (J·kg\(^{-1}\)), the efficiency of the heating system and the cooling performance coefficient, respectively. In this case, the total annual energy cost is written as follows.

\[
C_A = C_{AI} + C_{AS}
\]

The total cost of an insulated building is calculated using the following equation.

\[
C_T = C_A \cdot PWF + C_y \cdot x_y,
\]

where \( C_y \) and \( x_y \) are the price (\$/m\(^3\)) and thickness of the insulation, respectively. \( C_A \) is the sum of the annual heating and cooling costs per unit surface. When determining the optimum insulation thickness, the total heating cost over N-year life should be evaluated together with the present value factor (PWF). The PWF is calculated as follows depending on the interest rate \( (i) \) and the inflation rate \( (g) \) [11, 18, 20].

\[
PWF = \frac{1 + r}{i - g} - \frac{1}{r(1 + r)^N}, \quad i > gr
\]

The insulation thickness that will minimize the total cost gives us the optimum insulation thickness. Accordingly, the optimum insulation thickness is obtained by taking the derivative of the equation that gives the total cost according to the insulation thickness \( (x) \), as follows.

\[
x_{opt} = 293.94 \sqrt{\frac{PWF \cdot k}{C_y} \left( \frac{C_f \cdot HDD}{H_u \cdot \eta} + \frac{C_e \cdot CDD}{3.6 \times 10^6 \cdot COP} \right) - k_y \cdot R_{wt}}
\]

The payback period is calculated with the help of the following equation:

| Table 2 | Heating and cooling degree-day value according to Konya and Sivas |
|-----------------|-----------------|---------------------|
| Climate zone and city | Heating degree-day value (HDD) | Cooling degree-day value (CDD) |
| 3rd Zone-Konya | 2507 | 480 |
| 4th Zone-Sivas | 3003 | 538 |
where $S_A$ is the annual savings and is calculated from the difference between the annual energy costs of the uninsulated wall and the insulated wall as follows [9, 23, 24].

$$S_A = (C_A)_{yalsz} - C_A$$  \hspace{1cm} (13) 

The properties of the fuels used for the calculations and other parameters are given in Table 3.

### 3 Results

Table 4 shows the type of insulation material, density, optimum insulation thickness, payback period, and annual savings. When Table 4 was examined, it was found that XPS performed best in terms of optimal insulation thickness for natural gas use compared to other insulation materials. Although the unit price of XPS material is higher compared to other insulation materials, its optimal thickness is lower than other insulation materials in all situations due to its low thermal conductivity.

Table 4 shows the optimum insulation thicknesses for EPS, XPS, glass wool and rock wool insulation materials. When comparing all insulation thicknesses and using natural gas as fuel, XPS provided the best results in terms of optimal insulation thickness, payback period, and annual savings. Figure 2a and b shows a comparison of the optimal insulation thicknesses of different insulation materials for Konya, which is in the 3rd climate zone, using coal and natural gas as fuel.

In Fig. 3a and b, a comparison of the optimum insulation thicknesses of different insulation materials for Sivas, which is in the 4th climate zone, when coal and natural gas are used as fuel is given.

When Figs. 2a, b and 3a, b, the optimal insulation thickness for XPS is better when EPS, XPS, glass wool and rock wool are used for Konya, which is in the 3rd climate zone, and Sivas, which is in the 4th climate zone. Comparing coal and natural gas in relation to these insulation materials, the optimal insulation thickness for coal increases. This is due to the lower calorific value and efficiency of coal compared to natural gas. This situation shows a similar situation with other insulation materials. In this case, when coal and natural gas are compared, it shows that the payback period of natural gas gives the best value of about 2.8 years for Konya. Also, when coal and natural gas are compared, it shows that the payback period of natural gas is the most favorable for Sivas with 3.1 years. The type of insulation should be determined depending on the area of use, service life, humidity, cost, and insulation thickness. Using the diagram
Table 3  Parameters used in the calculations

| Natural gas | Coal       | Electricity          |
|-------------|------------|----------------------|
| Price [S/m³] | 0.214      | Price [S/kg]         | 0.249                  |
| Hu [J·m⁻³]  | 34 526 × 106 | Hu [J·kg⁻¹]          | 29 307 × 106           |
| Yield [%]   | 93         | Yield [%]            | 65                     |
| COP         | 2.5        | Yield [%]            | 99%                    |
| Hu [J·kg⁻¹] | 36 00 648 × 105 | RWT [m²·K⁻¹·W⁻¹] | 0.6                   |
| Yield [%]   | 93         | Yield [%]            | 65                     |
| g [%]       | 8.5%       | g [%]                | 8.5%                   |
| i [%]       | 9.75%      | i [%]                | 9.75%                  |
| N [year]    | 10         | N [year]             | 10                     |
above, the type and thickness of insulation material that will provide the desired thermal comfort can be selected. When comparing the insulation materials, although the unit price of the XPS material is higher, its optimal thickness is lower than that of the other insulation materials in all situations due to its low thermal conductivity. Figure 4 shows the graph of the different insulation materials for the optimal insulation thickness and payback time when using natural gas and coal as fuel.

As can be seen from the graph, lower payback periods were calculated for natural gas and longer for coal in both climate zones. In graph, the highest payback period is from the glass wool, followed by the EPS, rock wool and XPS for two climate zones. Therefore, this clearly indicates that the payback period of insulation in XPS is more advantageous. The results of the optimum insulation thickness, savings and payback period are performed using two different climate zones. For both two climate zones, although insulation cost increases with increasing insulation thickness, the fuel cost decreases when

| Material                | Density (kg·m⁻³) | X optimum (m) | Payback period (year) | Annual savings (%) |
|-------------------------|------------------|---------------|-----------------------|-------------------|
| 3rd Climate Zone-Konya  |                  |               |                       |                   |
| Natural gas             |                  |               |                       |                   |
| EPS                     | 32               | 0.076         | 3.16                  | 52.4              |
| XPS                     | 32               | 0.037         | 2.84                  | 54.6              |
| Glass wool              | 100              | 0.082         | 3.32                  | 51                |
| Rock wool               | 150              | 0.051         | 3.01                  | 53.8              |
| Coal                    |                  |               |                       |                   |
| EPS                     | 32               | 0.092         | 3.33                  | 46.9              |
| XPS                     | 32               | 0.061         | 2.95                  | 49.2              |
| Glass wool              | 100              | 0.104         | 3.43                  | 46.4              |
| Rock wool               | 150              | 0.078         | 3.19                  | 48.8              |
| 4th Climate Zone-Sivas  |                  |               |                       |                   |
| Natural gas             |                  |               |                       |                   |
| EPS                     | 32               | 0.086         | 3.36                  | 57.1              |
| XPS                     | 32               | 0.044         | 3.07                  | 59.1              |
| Glass wool              | 100              | 0.092         | 3.42                  | 56.2              |
| Rock wool               | 150              | 0.058         | 3.18                  | 58.5              |
| Coal                    |                  |               |                       |                   |
| EPS                     | 32               | 0.098         | 3.47                  | 46.3              |
| XPS                     | 32               | 0.069         | 3.19                  | 49.6              |
| Glass wool              | 100              | 0.106         | 3.56                  | 45.1              |
| Rock wool               | 150              | 0.081         | 3.24                  | 47.2              |
Fig. 2 (a) Optimum insulation thicknesses for coal use of different insulation materials. (b) Optimum insulation thicknesses for natural gas use of different insulation materials

Insulation thickness is reached to optimum insulation thickness, that is, total cost is in minimum value. Also, optimum insulation thickness is maximum lifetime saving.
Fig. 3  (a) Optimum insulation thicknesses for coal use of different insulation materials. (b). Optimum insulation thicknesses for natural gas use of different insulation materials.
4 Conclusions

In this study, the thermal conductivity of closed-cell thermal insulation materials as a function of temperature and density variations is investigated using various insulation materials. Optimal insulation thicknesses, annual gains, payback periods, and environmental analyzes were calculated for the building heating of Konya, which is in the 3rd zone, and Sivas, which is in the 4th zone, with different wall models and fuel types that have application areas in Turkey. As a result of the calculations for the $k$ value of the insulation material for Konya, which is in the 3rd climatic zone, the optimum insulation thickness was found to be 0.076 m for EPS with a density of 30 kg·m$^{-3}$, 0.037 m for XPS with a density of 30 kg·m$^{-3}$, 0.082 m for glass wool with a density of 100 kg·m$^{-3}$, 0.051 m for rock wool with a density of 150 kg·m$^{-3}$. When coal is used as fuel, the optimum insulation thicknesses for EPS, XPS, glass wool and rock wool are 0.092, 0.061, 0.104, 0.078, respectively. As a result of the calculations for the $k$ value of the insulation material for Sivas province, which is in the 4th climate zone, the optimum insulation thickness for EPS with density of 30 kg·m$^{-3}$ was found to be 0.086 m, for XPS with density of 30 kg·m$^{-3}$ was found to be 0.044 m, for glass wool with density of 100 kg·m$^{-3}$ was found to be 0.092 m, for rock wool with a density of 150 kg·m$^{-3}$ was found to be 0.058 m. When coal is used as fuel, the optimal insulation thicknesses for EPS, XPS, glass wool, and rock wool are 0.098, 0.069, 0.106, and 0.081, respectively. Comparing the insulation materials, although the unit price of XPS material is higher, its optimal thickness is lower than the other insulation materials in all situations due to its low thermal conductivity.
conductivity. For these two regions (Konya-Sivas), annual savings of 54.6% and 59.1% and payback periods of 2.8 and 3.1 years, respectively, were determined when natural gas was used as fuel and XPS was preferred as insulation material. In view of these data, it was found that XPS is better than other insulation materials in terms of optimum insulation thickness when natural gas is used. Although the unit price of XPS material is higher compared to other insulation materials, its optimal thickness is lower than other insulation materials in all situations due to its low thermal conductivity.

Author Contributions Each author contributed equally.

Funding No support was received from any organization/person.

Data Availability Availability of data and material is clearly stated in the text.

Code Availability Suitable.

Declarations

Conflict of interest There are no conflict of interest/competing interests.

Ethical Approval Suitable.

Consent to Participate Suitable.

Consent for Publication Suitable.

References

1. T.T. Karadayı, İ Yüksek, Tesisat Dergisi 242, 90 (2016)
2. A.E. Gürel, Z. Cingiz, Sakarya Üni. Fen Bilimleri Enstitüsü Dergisi 15, 75 (2011)
3. M. Soğukoğlu, M. Vatan, İstanbul Aydn Üni. Dergisi 21, 13 (2014)
4. İ Kibici, İzodergi 118, 60 (2016)
5. M. Kozak, Ş Kozak, SDU Teknik Bilimler Dergisi 5, 38 (2015)
6. N.V.S. Raju, M.I. Reddy, M.A. Kumar, K. Ramji, Mater. Today Proc. (2018). https://doi.org/10.1016/j.matpr.2017.12.191
7. E.S. Zaini, M.D. Azaman, M.S. Jamali, K.A. Ismail, J. Sandwich Struct. Mater. (2018). https://doi.org/10.1177/1099636218758589
8. Ö. Kaynaklı, M. Kılıç, R. Yamankara deniz, TTMD Şhhi Tesisat Dergisi 65, 39 (2010)
9. M. Ertürk, Gazi Üniv. Mühendislik-Mimarlık Fakültesi Dergisi 31, 2 (2016)
10. S. Gustafsson, Energy Build. (2000). https://doi.org/10.1016/S0378-7788(00)00062-1
11. J. Yuan, C. Farnham, K. Emura, Sustainability (2017). https://doi.org/10.3390/su9101711
12. E. İşık, V. Tuğan, Int. J. Pure Appl. Sci. (2017). https://doi.org/10.29132/ijpas.328883
13. R. Layberry, Wiley Appl. Energy 86, 120 (2009)
14. A. Papadopoulos, Energy Build. (2005). https://doi.org/10.1016/j.enbuild.2004.05.006
15. R. Christenson, ASHRAE J. 44, 36 (2002)
16. J. Yu, C. Yang, L. Tian, D. Liao, Appl. Energy (2009). https://doi.org/10.1016/j.apenergy.2009.03.010
17. X. Liu, Y. Chen, H. Ge, P. Fazio, G. Chen, Procedia Eng. (2015). https://doi.org/10.1016/j.proeng.2015.09.072
18. M. Gölcü, A.Ö. Dombaycı, S. Abali, Gazi Üni. Müh. Mım. Fakültesi Dergisi 21, 639 (2006)
19. TS 825, Türk Standartları Enstitüsü, Ankara (2008)
20. M. Koru, Arab. J. Sci. Eng. (2016). https://doi.org/10.1007/s13369-016-2122-6
21. G. Feng, Y. Feng, L. Qiu, X. Zhang, Appl. Therm. Eng. (2022). https://doi.org/10.1016/j.appltherma
geng.2022.118624
22. L. Qiu, X. Zhang, Z. Guo, Q. Li, Carbon (2021). https://doi.org/10.1016/j.carbon.2021.02.105
23. M. Koru, E. Korkmaz, M. Kan, Int. J. Thermophys. (2022). https://doi.org/10.1007/ s10765-022-03071-4
24. A. Kürekçi, Tesisat mühendisliği 131, 5 (2012)
25. L. Qiu, Y. Ouyang, Y. Feng, X. Zhang, X. Wang, J. Wu, Int. J. Therm. Sci. (2021). https://doi.org/ 10.1016/j.ijthermalsci.2020.106781
26. L. Qiu, Y. Ouyang, Y. Feng, X. Zhang, Rev. Sci. Instrum. (2018). https://doi.org/10.1063/1.5052692

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Mehmet Kan

Mehmet Kan

mehmetkan@sdu.edu.tr

Mechanical Engineering Department, Engineering Faculty, Suleyman Demirel University, 32260 Isparta, Turkey