

**AN INVESTIGATION OF ONE-DIMENSIONAL  
TIME-DEPENDENT HEAT TRANSFER IN  
BUILDING ROOFS FOR DIFFERENT CLIMATIC  
CONDITIONS IN TÜRKİYE**

**A Thesis Submitted to the Graduate School of Engineering and Science  
of İzmir Institute of Technology in Partial Fulfillment of the  
Requirements for Degree of**

**MASTER OF SCIENCE**

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**by  
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# ABSTRACT

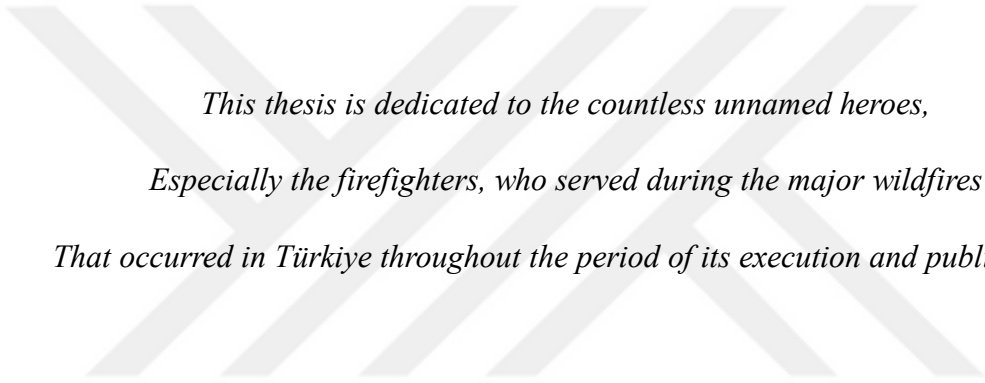
## AN INVESTIGATION OF ONE-DIMENSIONAL TIME-DEPENDENT HEAT TRANSFER IN BUILDING ROOFS FOR DIFFERENT CLIMATIC CONDITIONS IN TÜRKİYE

This thesis aims to evaluate the effect of roof type, slope angle, orientation and insulation level on heat transfer by analyzing the time-dependent one-dimensional heat transfer in residential roofs located in different climate zones. Within the scope of the study, six cities in Turkey with different climatic characteristics, two reinforced concrete roof types, two slope angles, four main orientations and four different insulation scenarios are considered. Insulation layers in roof systems are defined to provide the U-value requirements specified by the TS825 standard. Outdoor air temperature, solar radiation and effective sky temperature are defined as time-dependent outdoor conditions while indoor temperature is considered constant. The one-dimensional heat transfer problem is solved with an implicit finite difference method-based numerical model. Seasonal comparisons are made by analysing 24-hour periods of monthly-averaged daily data for January and July. The results show that both heat losses in winter and heat gains in summer decrease significantly as the insulation level increases. In the highly insulated scenario,  $q$  values decreased by 88-92% and a more stable temperature distribution was achieved indoors. Orientation-dependent differences were reduced to 4-10 Wh/m<sup>2</sup>-day, and current TS825 standard offered 4-10% improvement compared to old TS825 standard. Values for east and west-oriented sloping roofs are similar to those for south-facing roofs, while north-oriented 30° sloping roof differs from the other three orientations by about 6–46%. This highlights the importance of orientation-dependent optimisation strategies. The study shows that the combined evaluation of climatic, structural and orientation parameters is critical for energy-efficient roof design.

## ÖZET

### BİNA ÇATILARINDA BİR BOYUTLU ZAMANA BAĞLI ISI TRANSFERİNİN TÜRKİYE’NİN FARKLI İKLİM KOŞULLARI İÇİN İNCELENMESİ

Bu tez çalışması, farklı iklim bölgelerinde yer alan konut çatılarında zamana bağlı bir boyutlu ısı iletimini analiz ederek, çatı tipinin, eğim açısının, yönlenmenin ve yalıtım düzeyinin ısı geçişine etkisini değerlendirmeyi amaçlamaktadır. Çalışma kapsamında; Türkiye’de farklı iklimsel özellikleri olan altı şehir, iki betonarme çatı tipi, iki eğim açısı, dört ana yön ve dört farklı yalıtım senaryosu dikkate alınmıştır. Çatı sistemlerindeki yalıtım katmanları, TS825 standardının öngördüğü U-value gereksinimlerini sağlayacak şekilde tanımlanmıştır. Dış hava sıcaklığı, güneş ışıınımı ve etkin gökyüzü sıcaklığı zamana bağlı dış ortam koşulları olarak tanımlanırken iç ortam sıcaklığı ise sabit kabul edilmiştir. Bir boyutlu ısı transferi problemi, implicit sonlu farklar temelli bir sayısal yöntemle çözülmüştür. Ocak ve temmuz aylarının ortalamasını yansıtan 24 saatlik periyotlar incelenerek mevsimsel karşılaştırmalar yapılmıştır. Bulgular, yalıtım seviyesi arttıkça hem kış aylarında ısı kayıplarının hem de yaz aylarında ısı kazançlarının belirgin şekilde azaldığını göstermektedir. Yüksek yalıtımlı senaryoda q değerleri yalıtımsız duruma göre 88–92% oranında azalmış, iç mekânda daha kararlı bir sıcaklık dağılımı sağlanmıştır. Yönetime bağlı farklar 4–10 Wh/m<sup>2</sup>·gün seviyesine kadar düşmüş, mevcut TS825 standardı eski standarda göre 4–10% iyileşme sunmuştur. Doğu ve batı yönlenmeli eğimli çatılar; güneyle benzer değerler gösterirken, kuzey yönündeki 30° eğimli çatı ise diğer üç yönden yaklaşık 6-46% oranında ayrılmaktadır. Bu durum yönetime bağlı optimizasyon stratejilerinin önemini ortaya koymaktadır. Çalışma, iklimsel, yapısal ve yönetime bağlı parametrelerin birlikte değerlendirilmesinin enerji etkin çatı tasarımı açısından kritik olduğunu göstermektedir.



*This thesis is dedicated to the countless unnamed heroes,  
Especially the firefighters, who served during the major wildfires  
That occurred in Türkiye throughout the period of its execution and publication.*

*“Trees are poems that the earth writes upon the sky”*

*Khalil Gibran*

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## LIST OF ABBREVIATIONS

|          |                                                                            |
|----------|----------------------------------------------------------------------------|
| XPS      | : Extruded Polystyrene                                                     |
| HDD      | : Heating Degree Days                                                      |
| CDD      | : Cooling Degree Days                                                      |
| HVAC     | : Heating, Ventilating and Air Conditioning                                |
| TURKSTAT | : Turkish Statistical Institute                                            |
| ASHRAE   | : American Society of Heating Refrigerating and Air-Conditioning Engineers |
| TS       | : Turkish Standards                                                        |
| U-value  | : Overall Heat Transfer Coefficients in $W/m^2K$                           |
| TETD     | : Total Equivalent Temperature Difference                                  |
| TL       | : Time Lag                                                                 |
| DF       | : Decrement Factor                                                         |
| CFFT     | : Complex Finite Fourier Transform                                         |
| EPS      | : Extruded Polystyrene                                                     |
| RCC      | : Reinforced Cement Concrete                                               |
| PVGIS    | : Photovoltaic Geographical Information System                             |
| FDM      | : Finite Difference Method                                                 |
| TDMA     | : Thomas Tridiagonal Matrix Algorithm                                      |
| TSMS     | : Turkish State Meteorological Service                                     |
| EUROSTAT | : European Community Statistical Office                                    |
| PCM      | : Phase Change Materials                                                   |

## LIST OF NOMENCLATURE

|              |                                                                               |
|--------------|-------------------------------------------------------------------------------|
| $A$          | : Area [ $\text{m}^2$ ]                                                       |
| $C_p$        | : Specific Heat [ $\text{J/kg}\cdot\text{K}$ ]                                |
| $d$          | : Number of days                                                              |
| $h$          | : Convective Heat Transfer Coefficient [ $\text{W/m}^2\cdot^\circ\text{C}$ ]  |
| $I$          | : Solar Irradiance [ $\text{W/m}^2$ ]                                         |
| $k$          | : Thermal Conductivity [ $\text{W/m}\cdot\text{K}$ ]                          |
| $k/\rho C_p$ | : Thermal Diffusivity [ $\text{m}^2/\text{s}$ ]                               |
| $P_w$        | : Water Vapour Pressure [Pa]                                                  |
| $q$          | : Heat Transfer Rate [ $\text{Wh/m}^2\cdot\text{day}$ ]                       |
| $R$          | : Thermal Resistance [ $\text{m}^2\cdot^\circ\text{C}/\text{W}$ ]             |
| $T$          | : Temperature [ $^\circ\text{C}$ ]                                            |
| $T(x, y)$    | : $x$ Variable Represents the Location, $y$ Variable Represents the Time Step |
| $t$          | : Time [hour]                                                                 |
| $U$          | : Overall Heat Transfer Coefficient [ $\text{W/m}^2\cdot^\circ\text{C}$ ]     |
| $\Delta t$   | : Time Intervals [second]                                                     |
| $\Delta x$   | : Spatial Difference [milimeter]                                              |

**Greek Letters:**

- $\alpha$  : Absorptivity
- $\varepsilon$  : Emissivity
- $\rho$  : Density [kg/m<sup>3</sup>]
- $\sigma$  : Stefan-Boltzmann Constant [W/m<sup>2</sup>·K<sup>4</sup>]

**Subscripts:**

- 0 : The First Nodal Point Corresponding to the Outer Surface, or Initial Time Step
- $\infty$  : Values Far from the Surface
- in : Indoor
- ins : Insulation
- j : Nodal Point Throughout the Roof Slab
- L : The Last Nodal Point Corresponding to the Inner Surface
- n : Value Set of j
- o : Outdoor
- s : Surface

**Superscripts:**

- i : Time Step of Variable

# CHAPTER 1

## INTRODUCTION

In the last few centuries, humanity has experienced the fastest known technological revolution in its history and continues to do so at an ever-accelerating pace. The main factor that has contributed the most to this development is considered to be the Industrial Revolution. With this revolution, mechanisation and industrialisation progressed rapidly, leading to an increase in energy needs. As the population density and energy-consuming technologies have increased, the amount of energy required has also gradually increased. Due to the increase in energy consumption, the ecological balance has started to be damaged and the studies aimed at reducing this damage are increasing day by day.

The building sector accounts for approximately 40% of total energy consumption and associated Carbon Dioxide emissions, and energy consumption in residential buildings is increasing at an annual rate of 1.5%.<sup>1</sup> In the 21st century, due to the increasing energy demand and the greenhouse effect caused by the use of fossil fuels, there is a global temperature increase problem. This problem, which is called global warming, threatens not only the ecological balance but also the human generation in the long term. The most effective way to reduce these problems is to use energy more effectively and obtain it in a cleaner way.<sup>2</sup> Energy efficiency and sustainable energy definitions have emerged with the problems arising from energy consumption.<sup>3</sup> In this context, policies based on energy efficiency have started to be implemented in Türkiye, mainly in the European Union.<sup>4</sup> With these policies, many countries aiming sustainable developments have taken steps for the establishment of sustainable cities.

With the development of computers and the internet environment, people have become able to carry out their own work from their homes, and as a result of these developments, people spend time in their homes and the energy consumption of these structures have increased almost to the industrial level.<sup>5</sup> Due to the population agglomeration in urban areas, the use of materials with high heat absorption coefficient

in the building envelope and the city layout that reduces the wind effect, urban heat islands are formed.<sup>6</sup> Holding the temperature in the inner city higher than the outer part of the city, this phenomenon contributes approximately 30% to global warming.<sup>7</sup> Hence, the cooling loads of the buildings in the inner regions of the cities, especially those air-conditioned with Heating, Ventilating and Air Conditioning (HVAC) systems, increase considerably.<sup>8</sup> According to the data published by the Turkish Statistical Institute (TURKSTAT) in 2022, 65.3% of building energy consumption in Türkiye is consumed for heating purposes.<sup>9</sup>

Many organisations around the world are developing the necessary research and standards to optimise these energy consumptions. Such standards as; American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard-55 and Turkish Standard 825 (TS825) can be given as examples. Within the scope of this thesis, ‘Turkish Standard 825-Thermal Insulation Rules for Buildings’ standard was used in the selection of cities in different climatic regions and in determining the overall heat transfer coefficient (U-value) values.

In order to reduce energy consumption within the scope of the building, buildings should be classified according to their intended use and needs. Following this classification, necessary insulation applications are made and passive design strategies are integrated into the building. This approach is recommended by many studies to make buildings more sustainable. In projects designed with the aim of sustainable construction, even the improvement made in only one system can be effective on energy efficiency. However, researches reveal that arrangements made in more than one system provide higher energy savings by significantly reducing the heat transfer rate.<sup>10</sup> For example, in warm and temperate climates, heat gains due to solar radiation can be passively reduced by means of highly reflective roofing and cladding materials. In addition, the use of double or triple glazing with lower U-values in window systems increases energy efficiency by reducing thermal transmittance. As in this study, optimising the thickness of roof insulation, selecting highly reflective surface materials and identifying layers with strong insulation performance are critical for energy performance.

The main heat transfer surfaces in buildings are walls, windows, floors and roofs. In residential buildings, heat transfer rates from these surfaces can be approximately sorted as 30-60%, 10-25%, 10% and 25% respectively.<sup>11</sup> Therefore, studies to improve

the thermal performance of any building element are important for any building element. Roofs, which are among these elements, are more frequently and directly exposed to solar radiation compared to others. Roof is a building element that has an effect on indoor thermal comfort by protecting the buildings from physical factors such as solar radiation, wind, rain, snow, etc. by being located at the top level of the buildings in general. This structural element can enhance energy efficiency by regulating solar radiation and air flow. This is achieved not only through its material properties but also through its form, orientation and inclination.<sup>12</sup> While such designs and developments provide the indoor thermal comfort level of a building; they provide energy savings by causing a reduction in the total amount of energy required.

## **1.1. Research Framework and Problem Description**

TS825 provides a simple solution method for the calculation of heating loads in buildings in Türkiye and ensures nationwide applicability. This standard divides Türkiye into 4 different climate zones. The upper limits of U-value determined for different climatic regions indicate the basic insulation conditions that building elements must provide in order to ensure better energy performance. During the process of this thesis study, the TS825 was updated and the number of climate zones was increased to 6 and improvements were made in the required U-values. Considering the calculation method of this standard, the calculations are independent of time; It is made with stable constant internal and external temperature values representing monthly averages. With time-dependent (Transient) heat transfer analysis; it is possible to examine the effects of external parameters (solar radiation, temperature, relative humidity, wind speed) on the temperature distribution and heat transfer within the material and to obtain more accurate results.

In this thesis, time-dependent one-dimensional heat transfer on building roofs is the subject of investigation. This form of heat transfer is significant in terms of the total heat transfer in buildings, and is one of the important factors of energy consumption, due to the high degree of interaction with solar radiation when compared with other building surfaces. The implicit numerical approach method is utilised to calculate the time-dependent one-dimensional heat transfer on building roofs, and the temperature

distributions and heat transfer rates of different roof types are investigated. The parameters in these calculations can be listed as cities in different climatic regions of Türkiye, roof types and slope angles suitable for these roofs, roof orientations and insulation thicknesses.

At the time this thesis was conducted, TS825 ‘Thermal Insulation Rules in Buildings’, which is the basic standard for building energy performance, had not yet been updated. During the later stages of the study, important changes were applied to the standard. The number of climate zones has been increased from four to six, a method that includes the cooling load has been adopted instead of the approach that only considers the heating load, and improvements have been made to increase energy efficiency in the U-value limits determined for building components. In the climatic assessments carried out within the scope of the thesis, six different cities were identified in parallel with the new version of TS825 in order to represent Türkiye's climatic diversity more accurately. Each city was analysed using the average of 5 years of meteorological data <sup>13</sup> covering the years 2019-2023, taking into account the unique climatic conditions of these cities. In this context, the selection of cities both covers the six climate zones corresponding to the updated standard and shows the extent to which the research is in line with current scientific requirements. The cities analysed in the study are presented below:

- Ankara
- Antalya
- Ardahan
- İstanbul
- Sivas
- Şanlıurfa

There are many roof types and roof details used in Türkiye due to climate diversity. Each roof type may have advantages compared to the other in different climatic zones. The roof types selected in this research were chosen among the most common roof types in the country. There are two different roof types considered in this research:

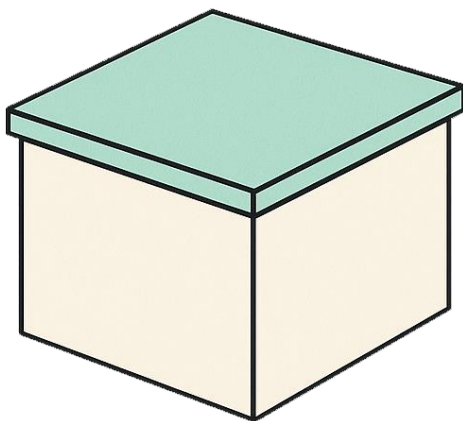
- Flat Terrace Roof
- Concrete Structure Roof

The angle of inclination of the concrete structure roof is  $30^\circ$  with reference to the horizontal, whereas the terrace roof has a flat, horizontal shape of  $0^\circ$ .

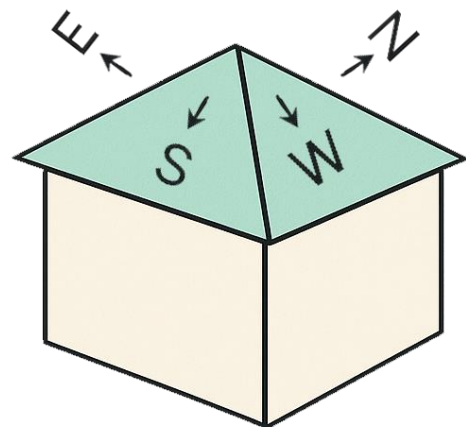
In this thesis, calculations for Concrete Structure Roof were performed for 4 different main directions in order to better understand the temperature distribution along the material according to time and directions and to determine the heat transfer effect. The four main directions for calculations are as given below:

- North
- East
- South
- West

The solar radiation, which varies depending on the direction, is a pivotal factor in the heat transfer of roofs, directly impacting their energy consumption. Since there is no directional change in solar radiation due to the roof angle of  $0^\circ$  in the flat terrace roof type, there is no directional analysis in this roof type. According to all of these, Approaches to four different directions for roofs and flat terraces are schematically illustrated in Figure 1.1.



Flat Terrace Roof



4-Oriented Roof

Figure 1.1. Schematic Representation of a Flat Terrace Roof and a 4-Oriented Roof

One of the primary methods employed to reduce heat transfer is the utilisation of a material that exhibits resistance to heat transfer on the transfer line. In other words, the objective is to create additional thermal resistance by applying thermal insulation. TS825 specifies the minimum heat transfer resistances that building elements should provide for four different climate zones in the first version and for 6 different climate zones in the new version. In this thesis, the location of the insulation materials along the roof cross-section is fixed but a parametric study is performed between four different insulation thickness scenarios. In this case, the insulation condition is classified in four different ways as shown below:

- Non-insulated
- Insulated depended by old TS825<sup>14</sup>
- Insulated depended by current TS825<sup>15</sup>
- Insulated with high resistance values based on UK Building Regulations<sup>16</sup>

The application of these classifications will facilitate the comparison of heat transfer rates and energy consumption values according to insulation thicknesses and internal surface temperature values. It is important to note that these parameters have a significant impact on thermal comfort. In the roof types under consideration, which will be calculated for all other scenarios, a comparative evaluation will be made between uninsulated, insulated and insulated-high resistance insulation. In the insulation parameters listed above, Insulated by old/current TS825 and Insulated with high resistance value, respectively, refer to the roof feature with the limit resistance value required by the standard and the roof features that we expect to have high thermal performance created with a wide insulation material such as 22 cm.

In this study, time-dependent heat transfer calculations will be performed for both roof types and heating/cooling loads will be calculated based on monthly average daily data. The capacity of HVAC systems are determined by the accurate calculation of heating and cooling loads. It is anticipated that these capacities will be adequate in meeting power requirements even under the most challenging conditions. Consequently, when calculating the load, calculations are made for both the lowest and highest conditions. It is evident that the devices selected for the resulting heating and cooling loads are compatible with the most demanding conditions. The aim here is to provide continuous

thermal comfort of the interior space regardless of the difficulty of external conditions. Together with this situation, it is possible to determine the energy consumption values of heating and cooling systems by using long-term average climate data. While periodic deviations from average values are compensated by the correct system capacity selection, long-term energy consumption should be calculated on the basis of average climate values. For the aforementioned reasons, the data from January and July were utilised for heating and cooling loads, respectively. The selection of these cities and months was based on the determination of the lowest and highest outdoor temperatures and solar radiation rates.

In this thesis study, six cities representing the six distinct climate zones of Türkiye, two roof types, including a flat terrace and a 4-oriented sloped roofs, with four orientations, and four insulation scenarios, including an uninsulated case and three different insulation levels, were evaluated. The calculations were carried out for two representative months, January for the winter season and July for the summer season. In total, 240 different scenarios were analysed based on the combination of these parameters.

## **1.2. Aim of Thesis**

The main objective of this thesis is to investigate the time-dependent thermal performance of roofs, which are an important component of energy exchange in buildings and play a major role in energy consumption, especially due to their direct exposure to solar radiation. One-dimensional time-dependent heat transfer analyses of two common roof types selected for six cities representing different climatic conditions in Türkiye are conducted using the implicit numerical method with a finite difference approach. In the analyses, both uninsulated and roof scenarios with different insulation thicknesses were considered; these scenarios were diversified in line with national standards and high performance targets. As a result of these calculations using hourly climate data; temperature distributions along the roof layers, internal surface temperatures and heat transfer rates were determined, and energy performance and indoor thermal comfort level were evaluated with the findings obtained.

The aim of this thesis is to reveal the thermal effects of material compositions and insulation levels, as well as to provide recommendations for developing sustainable

design strategies. Thus, by optimising roof structures, contribution will be made to the reduction of heating and cooling loads nationwide.

In order to reduce energy consumption at national level, various policy and strategy documents have been developed in Türkiye. In this context, the 2nd National Energy Efficiency Action Plan published by the Ministry of Energy and Natural Resources targets a 16% reduction in energy consumption across the country until 2030. This directive, which is planned to reach the target figure with a variety of plans and projects, primarily includes the promotion of renewable energy sources and improvements in regulations throughout the country.<sup>17</sup> In this context, important updates have been made in the TS825 standard during the period when the calculations were conducted within the scope of the thesis. While the standard previously included four climate zones, this number has been increased to six, and the U-value values of the building elements for each zone have been reduced to increase energy efficiency. The cities considered in the study correspond to this new classification, thus making the analyses more compatible with the current regulation targets. Furthermore, in this thesis, not only performance analyses were performed, but also the effects of changing limit values on building energy performance were compared by comparing the old and new TS825 standards.

In summary, the main objective of this thesis is to evaluate the effects of parameters such as orientation, climatic variables and roof slope on the thermal performance of roofs in cities representing six different climate zones of Türkiye. By analysing the temperature distributions along the roof layers and interior surface temperatures, the effects on indoor thermal comfort are studied in detail. Besides, by comparing roof systems with different insulation thicknesses, the effects of optimum insulation levels on energy consumption are revealed. The objective of the present study is to undertake a comparative analysis of the effects of the old and current versions of the TS825 standard on building energy performance. In accordance with the aforementioned evaluations, the objective is to contribute to sustainable building design by developing roof design and insulation strategies that are compatible with the diverse climatic conditions of Türkiye.

### 1.3. Literature Review

Kaşka et al.<sup>18</sup>, developed both an experimental and theoretical model to investigate the time-dependent heat conduction in multilayer structural elements. The theoretical model is based on a one-dimensional system of time-dependent parabolic differential equations in which the individual heat conduction equations defined for each layer are solved with convective boundary conditions on the inner and outer surfaces. The experimental system was set up in two test chambers, each consisting of different wall and roof materials, and the temperatures were measured in minutes. The concordance between the theoretical results obtained with the developed model and experimental measurements was tested and the validity of the model was verified with error rates less than 5%. According to the results of the study, autoclaved aerated concrete and blockbims used as building components reduce heat transfer by 18% to 22% compared to brick and briquette materials. These findings reveal heat gains, which directly affect the cooling load during the summer period, are sensitive to material selection.

Kaşka et al.<sup>19</sup>, compared the total equivalent temperature difference (TETD) values for multilayered wall and roof systems with theoretical models and field experiments. TETD calculations were based on parameters such as time lag (TL) and decrement factor (DF), which were obtained in response to outdoor temperature and solar radiation. The study analysed eight different wall types and two roof types. The results showed that while TETD values were measured between 32 and 38 °C in uninsulated building shells, these values decreased to between 19 and 24 °C in insulated walls. Additionally, it was noted that time lags of up to 2 hours were observed in walls with high heat capacities, which delayed the transfer of heat to the indoor environment during daylight hours and reduced the cooling load.

Yumrutaş et al.<sup>20</sup>, developed a mathematical model based on CFFT in order to determine the TETD values of multi-layered walls and roofs for different climate zones by analytical methods. The model calculates the temperature distribution and internal surface temperatures for each layer under time-dependent external environmental conditions (temperature and radiation). In the applications made for 43 cities in Türkiye, it was found that the TETD values varied between 18–40°C depending on the type of roof and wall. It was observed that DF decreased to 0.3% in high-density building materials,

while this rate increased to 0.6% in low-density materials. These differences emphasize the effect of material selection in determining the thermal response of building elements.

The model developed by Yumrutaş et al.<sup>21</sup> in this study is based on the CFFT method for the analytical solution of transient heat transfer equations that define heat transfer in multilayered building components. The solution structure of the model is based on hyperbolic functions that determine the temperature field in each layer. As a result of the applications made for six different wall and two roof types frequently used in Türkiye, it was calculated that the interior surface temperature in uninsulated roof types follows the exterior air temperature with only a 1-hour delay, whereas this period is up to 3 hours in insulated roofs. In addition, it was observed that 25% higher heat gain occurred in reinforced concrete roofs compared to traditional solutions. This situation reveals the effect of the thermal mass of the structure and the layer order on the heat gain.

Although these four studies are based on similar theoretical foundations for modelling transient heat transfer in multilayered structural components, they differ in certain respects in terms of their use of analytical and experimental methods. While the studies conducted by Yumrutaş et al. in 2005 and 2007<sup>20,21</sup> focused on estimating the internal surface temperature and heat gains of building elements over time using analytical models developed with the CFFT method, the studies conducted by Kaşka et al. in 2008 and 2009<sup>18,19</sup> contributed to field validity by verifying the same type of mathematical models with experimental data. The common point of all these studies is that they address performance parameters such as TETD, time lag, decrement factor and examine the relationship between the material properties of the building envelope and climatic data. However, the first group of studies mentioned here mainly focused on flat wall and roof systems; they did not include extended scenarios that include many parameters such as roof slope, orientation-dependent variability, radiative effects or economic dimensions of insulation. Therefore, different climate, roof type, orientation-dependent analyses and models supported by passive strategies published in the literature in recent years have diversified this theoretical framework further and prepared the ground for more realistic applications. These current studies summarised below provide a more comprehensive assessment in the field of building roofs and directly contribute to the framework of this thesis study methodologically and thematically.

Daouas<sup>22</sup> investigated the effect of external Long-Wave Radiation on optimum insulation thickness on flat roofs in the Tunisian climate. In the study, an analytical model based on Complex Finite Fourier Transform (CFFT) was developed and a life-time cost analysis was performed by calculating hourly heat flux for different insulation materials and roof types. According to the results, when the Long Wave Radiation effect is not taken into account, optimum insulation thickness and energy saving rates are estimated incorrectly; for example, while 58% saving is achieved with stone wool insulation, the optimum thickness is determined as 7.9 cm.

Kaçan et al.<sup>23</sup>, evaluated the effects of optimum thermal insulation scenarios that can be applied to the existing building stock in Türkiye on energy consumption and emission values. In the study, insulation thicknesses were determined according to the TS825 standard for sample buildings representing four degree-day regions based on the Turkish Statistical Institute data and the building energy requirement was calculated according to different fuel types. As a result of the analysis, it was observed that the application of insulation provided a reduction of 28% to 80% in Carbon Dioxide and Sulfur Dioxide emissions, respectively. It was determined that optimum insulation thicknesses varied between 6 and 16 cm depending on the climate zone. The study is notable for its comparative analysis of the environmental benefits of insulation at a regional level.

Arumugam et al.<sup>24</sup>, aimed to determine the optimum insulation thickness for roofs with high reflective cold cladding (albedo=0.6) and low emissivity radiant barrier ( $\epsilon=0.2$ ) in five different climatic zones of India. A total of 88 roof combinations were analysed on a 200 m<sup>2</sup> single-storey office building model with EnergyPlus software and an economic evaluation was made with the internal rate of return. According to the results, the recommended optimum R-values for hot and dry climates were determined as 0.49 m<sup>2</sup>°C/W, for temperate and humid climates as 0.31 m<sup>2</sup>°C/W, and for cold climates as 1.02 m<sup>2</sup>°C/W. This study is remarkable in terms of evaluating the thermal performance of roof elements together with economic analysis.

Pekdoğan and Başaran<sup>25</sup> investigated the effects of wall orientation and insulation layer location (interior, exterior, middle) on time-dependent heat transfer behaviour in different climate zones of Türkiye. One-dimensional time-dependent heat transfer equation was solved by the implicit finite difference method, and average external climate

data for January–July months were used for four cities. Solar radiation and external air temperatures that vary according to orientation were taken into account as external surface conditions. Calculations showed that heat gain and loss in sandwich wall systems were lower than other insulation types both in summer and winter periods; also, heat transfer variability due to orientation became more pronounced in summer period. This study makes an original contribution to the literature by numerically comparing both the orientation effect and insulation location under dynamic conditions.

In the study conducted by Al-Sanea<sup>26</sup> the transient thermal performances of six different roof types used in the climate conditions of Riyadh, Saudi Arabia were comparatively investigated. In the study, a numerical model based on the one-dimensional control volume method was developed under the conditions of time-dependent external temperature, solar radiation and nonlinear radiation variation. According to the results, the 5 cm thick polyurethane insulation layer reduced the heat transfer load by 77% compared to the uninsulated roof. In addition, positioning the insulation closer to the inside reduces sudden loads but exposes the waterproofing layer to greater temperature changes.

In the study conducted by Orhan and Bektaş Ekici<sup>27</sup>, the effects of hipped, terrace and green roof types on building heating and cooling loads in five different climate zones of Türkiye (Hatay, Bursa, Elazığ, Sivas, Kars) were comparatively analyzed. In the simulations conducted with DesignBuilder software, only the roof type was changed with fixed building geometry and energy loads were calculated for each scenario. According to the findings, green roofs reduced both heating and cooling loads in all regions; especially in the hot climate region such as Hatay, they provided a 6.7% improvement in heating load and a 2.7% improvement in cooling load. Terrace roofs generally resulted in higher energy consumption.

Askar et al.<sup>12</sup> investigated the effect of roof slope on building thermal performance in different climatic conditions. Roof configurations selected for Miskolc (temperate) and Baghdad (hot) climates were evaluated using HAP and ANSYS Fluent software, both hourly and time-dependent analyses. Trombe wall and glass wool insulation applications were also tested in the study, together with optimum roof slope. The results showed that sloped roofs provide heat gain/loss reductions of up to 45% in summer and 10% in winter compared to horizontal roofs.

Tong et al.<sup>28</sup> investigated the effects of passive roof technologies (cold coating paint, ventilation, Extruded Polystyrene (EPS) insulation, radiant barrier) on thermal performance of multi-layered concrete roofs in tropical climate conditions. In the study, the analytical model developed with the Complex Fast Fourier Transform method was validated with field measurements on two real-scale roofs and then used in parametric analyses. According to the results, an increase in the reflectivity of the roof surface by 0.1 reduces the daily heat gain by 11%; when used with EPS and radiant barrier, a total reduction of up to 84% is achieved.

Liu et al.<sup>29</sup> developed a time-dependent spectral heat transfer model to evaluate the annual energy saving performance of radiative cooling coatings in three different climate zones of China. The developed model was validated by experimental data and it was shown that radiative cooling coatings reduced the annual roof load by 84.9%, 30.3% and 2.4% for Guangzhou, Shanghai and Beijing, respectively. The results showed that reflectivity was the more decisive factor in tropical climates, while insulation thickness was the more decisive factor in temperate and cold climates.

Rawat and Singh<sup>30</sup> conducted an experimental study in cube-shaped test chambers with 61 cm side dimensions in the mixed climate zone of Indore, India, comparing the thermal performance of a high reflective cool roof coating (albedo = 0.88) with a reinforced cement concrete (RCC) roof. As a result of field measurements conducted in April–May, it was determined that the cool roof reduced the indoor temperature by an average of 2.4°C, the roof interior surface temperature by 4.1°C and the exterior surface temperature by 9.2°C. Although the study was conducted on a small-scale test cell, it shows that cool roofs have significant potential, especially in terms of low-cost and easily applicable passive solutions.

Zingre et al.<sup>31</sup> developed a unique mathematical model called Cool Roof Heat Transfer based on the spectral approximation method to evaluate the thermal effects of cold coating application for concrete and metal roofs under tropical climate conditions. The model was validated with experimental data and was shown to reduce the roof surface temperature by 14.1 °C, the indoor temperature by 2.4 °C and the daily heat gain by 54% especially on sunny days.

Xu et al.<sup>32</sup> conducted an experimental study in Guangzhou, China, to evaluate the impact of applying cold materials to different floors of buildings on the indoor

environment, building surfaces and street microclimate. Experiments with 100 scaled building models revealed that applying cold materials to the roof reduced the surface temperature by 13.5 °C and the indoor temperature by 3.9 °C. When applied to the facades, the indoor temperature decreased by an average of 0.5–1.9 °C, depending on the floor height. The maximum change in street air temperature was 0.2 °C.

The studies summarised above present a large number of analytical, experimental and simulation-based approaches to assess the performance of the building envelope and examine the effect of parameters such as roof material, insulation thickness, orientation, slope and climatic conditions on energy loads in limited combinations. However, the majority of these studies are confined to flat roofs; multi-parameter analyses which evaluate roof slope, orientation-dependent insulation differences, insulation variations and U-value requirements based on TS 825 standard are rarely included in the extant literature. Furthermore, the impact of roof systems with varying slope angles and orientations on seasonal heat loss and gain remains largely unexplored. In order to fill this gap, this thesis comprehensively analyses four different insulation levels for different climate zones, including flat surface and 30° sloped roofs, four main directions, uninsulated case, as well as insulated alternatives and highly insulated scenarios based on old and new versions of TS825. The TS825 standard has been updated during the thesis process, thus enabling the study to provide a comparative evaluation by making separate calculations according to both versions. Furthermore, the calculations encompassed not only the primary building materials but also all components, including membrane layers with a thickness of up to 3 mm. In this regard, the study's level of detail in material composition and heat conduction analysis is distinct from that of analogous studies in the literature. As a conclusion, this thesis provides both a technical contribution to the design process and a data-based support to Türkiye's climate-oriented building energy policies by presenting a multifaceted approach that considers geometry, orientation, climate and insulation parameters together, considers one-dimensional time-dependent heat transfer and presents realistic scenarios based on TS825.

## 1.4. Contents of Thesis

In this thesis, firstly, the effects of the building sector on energy consumption are discussed and in this context, the concepts of sustainability and energy efficiency developed in response to increasing energy demand are discussed. The importance of policies and standards established with the aim of energy efficiency is emphasised and new requirements arising from the update of the TS825 standard in application in Türkiye are mentioned. In Chapter 1, the importance of this thesis and the field of study is emphasised by examining the current similar researches in the literature.

In Chapter 2, the methodological background of the study is presented and the numerical solution approach used in time-dependent one-dimensional heat transfer calculations is explained. Then, in Chapter 3, the implicit method used in the calculations and its solution are explained in detail. In addition, the stability properties of this method and the reasons for its preference are detailed and information about the integration of the method into the software is given.

Then, Chapter 4 details the roof typologies, material layers used in these roofs and thermal properties within the scope of the scenarios considered in the study. The effects of orientation, roof slope and insulation thicknesses on heat transfer are analysed in the evaluations made on the cities selected to represent the six updated climate zones of Türkiye.

Subsequent to this, the results obtained in Chapter 5 on temperature distribution, internal surface temperature and heat transfer rates are analysed; the thermal performance of roofs under different climatic conditions, orientations and insulation scenarios are comparatively evaluated and their effects on energy consumption are presented. Furthermore, the results of the analyses performed according to the old and new versions of TS825 are compared and the effects of the changes in the standard on the performance are explained with solid data.

Finally, the findings obtained from the calculations are subjected to a general evaluation, future study recommendations and the potential for the results to inform architectural design and energy policies is discussed in Chapter 6.

## CHAPTER 2

### METHODOLOGY

Under this chapter of the thesis, the method of the research, the data collection process, how the data obtained were evaluated, the sources of the collected data, the basics of the heat transfer calculation method focused on the problem of the thesis and the mathematical model that forms this basis are mentioned.

In this thesis, for six different cities in different climatic conditions in Türkiye, the time-dependent one-dimensional heat conduction equation along the roof materials of two different roof types is analysed with a numerical approach. Based on these analysed values, the heat transfer rates entering/exiting the indoor space were calculated. The heat transfer rates are calculated separately for a total of four different cases for the uninsulated case and three cases with different insulation thicknesses, and then the values are compared. The numerical calculations were carried out using Microsoft Visual Basic 6.0, a high-level, event-based software program that provides ease of use because it allows user interface design.<sup>33</sup>

#### 2.1. Data Collection

The accuracy of the data used during calculations is of vital importance in order to perform calculations based on the laws of physics in a healthy way and to obtain accurate results from these calculations. The reason why time-dependent heat transfer is different from steady-state heat transfer is that the variables affecting heat transfer change for each time step, and accordingly thermal energy is stored in the material. In entering the changes in boundary conditions into the computer program prepared as data input, it is as important where and how these data are obtained as what the data are.

One of the important points of many research studies is to collect data. Outdoor temperature, Relative humidity, Sky Temperature and Solar radiation are the first data

collected in this thesis. For these data obtained as a result of long-term measurements, temperature and relative humidity values from the Turkish State Meteorological Services, which is part of the Ministry of Urbanisation and Climate Change of the Republic of Türkiye, were used and sky temperature values were determined. Solar radiation values were also obtained from the Photovoltaic Geographical Information System (PVGIS), a program developed by the European Commission and made available to the public. In addition, the Heating Degree Day (HDD) and Cooling Degree Day (CDD) values of the provinces in Türkiye published by the Meteorological Services and the maps of the country and citywide average solar radiation published by the General Directorate of Meteorology were also important parameters for the six different cities selected in this thesis.

### **2.1.1. Turkish State Meteorological Service's Data**

Located in the subtropical climate zone between 36-42° north latitude and 26-45° east longitude, Türkiye has a very rich climate diversity compared to its surface area. A study analysing the HDD and CDD values at the borders of the country clearly shows that the most affected parameters of outdoor temperatures are the height of the region above sea level rather than the latitude and longitude. Therefore, it is important for the research to select regions that reflect different climatic zones in the outdoor data obtained.<sup>34</sup>

The outdoor temperature and outdoor relative humidity data used in this thesis are provided by the Meteorological Services and include continuous data for a total of five years, from 2019 to 2023. In case of possible incompleteness of these data collected from multiple stations, the margins of error for several time steps are complemented with appropriate values by interpolation after checks by the system.<sup>35</sup> These data were first converted into one-year average data, which will be the average of five years, and the months of January for the winter season and July for the summer season were determined where the temperature reached the maximum and minimum points. Then, the monthly averages were converted into daily temperature format and the temperature values were determined for the required time steps by linear interpolation before calculation.

Sky radiation plays an effective role in the long-wavelength heat radiation from the building envelope to the atmosphere, especially on horizontal planes such as roof surfaces. Accurate assessment of this radiation has a critical role to accurately estimate the total heat loss through the building envelope. Therefore, sky operative radiative temperature ( $T_{sky}$ ) calculations are one of the key inputs in thermal comfort and energy efficiency analysis. Although different models are used in the literature to estimate the effective radiative temperature of the sky, studies show that the amount of humidity, i.e. water vapour pressure ( $P_w$ ), has a direct effect on this temperature. In 1982, Melchor and his colleagues showed that the effect of water vapour pressure on  $T_{sky}$  is stronger and that the calculations taking this parameter into account give more realistic results. Accordingly, the formula given in Equation 2.1 is used for sky temperature estimation in this thesis.<sup>36</sup>

$$T_{sky} = T_{air} (0.56 + 0.08 \cdot \sqrt{p_w})^{0.25} \quad (2.1)$$

In this formula,  $T_{air}$  represents the outside air temperature, and  $P_w$  represents the water vapour pressure. Due to the water vapour effect in the formula, it is possible to evaluate radiative heat losses more accurately in humid climatic conditions. Therefore, this approach was preferred for its convenience in the hot and humid climatic regions where this study was conducted.<sup>37</sup>

### 2.1.2. Photovoltaic Geographical Information System (PVGIS)'s Data

With the Photovoltaic Geographical Information System developed by the European Commission and made available for open access, solar radiation values, which are used in heat transfer calculations and are important as a boundary condition, are obtained. The main database of this system consists of images obtained at regular intervals from satellites such as METEOSAT, whose class is geostationary meteorology. These satellites provide regular data from the Asian, African and European continents of the world with lower and upper limits of 15 to 30 minutes, respectively. This system analyses the images on a pixel basis and calculates the amount of solar radiation by

comparing the defined pixel values with those of other days. Then the darkest pixel is assigns as the region with the lowest reflectivity. Then the effective cloud albedo is determined pointwise. This system has a holistic calculation method that takes into account not only water vapour, aerosols and ozone in the atmosphere but also topographic features. The solar radiation amounts calculated by this system are quite significant, but the calculations are biased due to the high white area (high albedo) in snowy regions and in regions other than Asia, Africa and Europe, where satellites are centered to collect images.<sup>38</sup>

In this thesis, solar radiation data were obtained from the system by entering each direction and angle values and solar radiation amounts were taken with the local time of the city. While obtaining these data, the PVGIS-SARAH 3 system in the data bank containing data until 2024 was used. These data were obtained as monthly average daily data, one for each hour, i.e. a total of 24 daily data, then the other time steps required were linearly interpolated between these values.

In this study, the “G(i)” parameter, referring to global irradiance on a fixed plane, was used. For each orientation, the azimuth value was individually defined, and radiation values were retrieved for surfaces with a 30° slope. The PVGIS interface allows for the specification of slope and orientation and calculates direction-dependent irradiance accordingly. In these calculations, the conversion of global horizontal irradiance to inclined surface irradiance is performed using transposition models. These models consider the sun’s position, slope, and azimuth to determine the amount of radiation received on tilted surfaces. This calculation method only considers low-range radiation waves, representing direct solar radiation. Additionally, the system’s long-term average cloudiness archive was used, and the second of the two cloudless sky assumptions representing historical average conditions was selected. By integrating directional and angular differentiation with localised time-based data, the boundary conditions for each city and orientation were accurately and consistently represented.

### 2.1.3. Materials Thermal Properties

In order to perform transient heat transfer calculations, the thermophysical properties of a materials must be known. The material properties required for time-dependent one-dimensional heat transfer calculations where there is no flow problem are; thermal conductivity ( $k$ ), density ( $\rho$ ) and specific heat ( $C_p$ ) and diffusivity ( $k/\rho C_p$ ) calculated by using these three values. In addition, absorptivity ( $\alpha$ ) and emissivity ( $\varepsilon$ ) values are also required to use solar and thermal radiation values.

These material properties are directly related to transient heat transfer. Materials with higher thermal conductivity values conduct heat faster, while materials with lower thermal conductivity values conduct heat more slowly. It is important to choose the appropriate material in terms of thermal design. For example, in hot and temperate climates, materials with low absorptivity and high emissivity values can be preferred in the coatings of buildings in regions that consume more energy for cooling purposes due to solar radiation gain, as they will passively reduce energy consumption.<sup>32</sup> Apart from using insulation materials, it is also possible to control the heat transfer from/into the building by storing latent thermal energy in these materials integrated into the building element by using appropriate phase change materials selected according to the temperature norms of the region.<sup>39</sup>

The three different roof types used in the heat transfer calculations in this thesis research have a variety of materials and details. The material properties used in this research are taken from version 7.02.006 of the DesignBuilder program using the Energyplus 9.4 database.<sup>40</sup> These material properties are discussed in more detail under section 4.2.

## 2.2. Numerical Method of Transient Heat Transfer

One of the classifications used in heat transfer calculations is steady state and time-dependent analysis. Since the internal and external conditions are constant in steady-state heat conduction analysis, it is possible to calculate the results as an exact solution according to Fourier's Law. The temperature distribution along the material is linear in

such heat transfer calculations.<sup>41</sup> For this reason, the mathematical expression of time-dependent heat transfer differs from steady-state heat transfer.<sup>42</sup> Analytical solutions in time-dependent heat transfer are only possible for some boundary conditions and for some geometries.<sup>43</sup> On the other hand, numerical approaches are widely used in predicting the temperature distributions at each defined time step for different internal and external conditions and for different geometries. Under this title, the numerical approximation of the one-dimensional time-dependent heat transfer calculated in this thesis and the supplementary mathematical methods used in these calculations are discussed.

### **2.2.1. Numerical Approaching**

Numerical approaches are used to solve engineering problems for which there is no analytical solution. These problems do not have a definitive answer because complex situations arise when conditions change over time or in different locations. Thus, an approximate value is sought in such cases. Numerical approaches are widely used in mathematical calculations based on the laws of physics, such as structural analysis, fluid dynamics, and thermal simulations in engineering and physics.<sup>44</sup> Application area of this method is quite wide and it is frequently used not only in academic research but also in industrial areas.<sup>45</sup> It should be mentioned that the heat transfer rates calculated in this thesis are not 100% accurate due to the nature of the numerical approach. However, with a sufficient number of iterations of the calculation method, the margin of error was reduced below 0.01%.

In the solution of time-dependent heat conduction problems, the Finite Difference Method (FDM), which is one of the numerical solution techniques, is taken as a basis and the implicit method is preferred in the solution of time steps. This approach, when calculating the temperature distribution for each time step, takes into account not only the previous time steps but also the unknowns in the current time interval subject to the solution. Even though this method is more complex in terms of the computational process, it is preferred due to its ability to maintain the stability of the numerical solution even over larger time step intervals. On the other hand, it is necessary to use small time steps in the analysis with the explicit method. Otherwise, the conformity of the results to the physical reality may deteriorate and instability may occur in the solution. This increases

the computation time of the model and makes it difficult to achieve the desired accuracy in some cases. Therefore, in this thesis, the implicit solution method is applied in order to obtain more stable results and to ensure efficiency in the computation process.<sup>46</sup>

### **2.2.2. Finite Difference Method**

The finite difference method, one of the numerical methods, decomposes differential equations into computable bounded algebraic expressions. The calculation steps limited by the decomposition are processed respectively and the result is obtained. Thus, for each discretised point, the function values of the process and the difference equations, the combination of these values, are obtained.<sup>47</sup> These difference equations are successively directed to the solution and approximate values of the desired physical quantities are calculated. With this method, the geometry is divided into a finite number of nodal points and solutions are found depending on time and position. The obtained solution is transferred to matrix format.<sup>48</sup>

In this thesis, in order to perform one-dimensional time-dependent heat transfer calculations, the system is divided into a finite number of sections along the roof cross-section. With the help of these points, the partial differential equations are transformed into algebraic expressions. Thus, the temperature distribution along the roof section can be expressed in curvilinear graphs for different time steps. There is a linear interaction between the two discretised points. Therefore, a large distance between the differences can lead to errors in the calculations, as the temperature distribution that should change curvilinearly is represented linearly. In this thesis, each calculation step was determined to be 1 millimetre (mm). Thus, the step intervals are kept small and the accuracy of the results is increased.

In transient heat transfer calculations, the analysis is carried out over all time steps for each calculation point. In this process, the step size ( $\Delta t$ ) between two consecutive time intervals is critical for the accuracy of the temperature distribution and heat transfer rate results along the material. In the numerical method applied, temperature values and the associated heat transfer rate are calculated for each time step, and this process is continued iteratively to minimize the margin of error of the method. However, if the time step

interval is chosen too large, the results may not reflect the curvilinear behaviour of the time-dependent change sufficiently, and the results may be expressed in a linear structure. Therefore, choosing a suitable time step is one of the most important decisions to be made in numerical methods in order to keep the analysis significant in terms of both accuracy and computational efficiency. On the other hand, if the time step size is set smaller than the optimum range of time interval, the accuracy of the results will not increase in the decimal range where the results are evaluated, but the computation time and computational load will increase significantly. In this study, the time interval was determined by taking the average of the intervals specified in three different fundamental books.<sup>46,48,49</sup> According to all these considerations and assumptions, the time interval of 60 seconds (1 minute) is preferred for the calculations performed in this thesis.

### **2.3. Thomas Tridiagonal Matrix Algorithm (TDMA)**

In a finite difference discretisation calculus, calculations are performed on a matrix. The Thomas algorithm is a special form of Gaussian elimination specifically designed to solve tridiagonal systems of linear equations common in discretised Partial Difference Equations.<sup>50</sup> The number of columns of the matrix that will continue diagonally is related to the number of dimensions of the process. In cases where heat transfer is analysed in one dimension, the matrix is tridiagonal. The Thomas Tridiagonal Matrix Algorithm reduces the complex structure of Gauss Elimination with  $n^3$  operations to one dimension with  $n$  operations. This algorithm, which greatly reduces the solution time and computational load of the unknowns in the matrix, performs the forward elimination and back substitution operations of Gaussian elimination in a simplified manner.<sup>51</sup> In the heat transfer calculations of this thesis, the back substitution method of Gaussian elimination was preferred, and the final results were obtained. Back substitution is preferred for upper triangular matrix solutions because it is direct, fast, stable and computationally more efficient.

## **CHAPTER 3**

### **NUMERICAL MODELING OF TRANSIENT HEAT TRANSFER AND BOUNDARY CONDITION ANALYSIS**

This part of the thesis focuses on the numerical modelling of one-dimensional time-dependent heat transfer and the mathematical formation of boundary and initial conditions associated with this model, which is critical for understanding the heat flow in structural elements such as walls and roofs. In addition, the importance of U-value calculations and how these calculations are performed are discussed in detail. A detailed explanation of the Finite Difference Method used for solving heat transfer problems is also given and the discretization process and how the heat transfer equation is solved is explained step by step. Also, the solutions of the matrix equations resulting from this discretised system are explained. An overview of the numerical program that performs these calculations and presents the results is presented.

#### **3.1. Overall Heat Transfer Coefficient Calculation Method Based on TS825 Standart**

U-value refers to the amount of instantaneous heat transfer per unit area for a unit temperature difference in various building elements.<sup>15</sup> This value is very important for energy performance assessments and calculations in buildings. In terms of ease of calculation and practicality, it can be easily calculated even in different buildings. Thus, with this calculation method, it is possible to make designs that can meet the building energy performance standards for new buildings or buildings that will be renovated. Under this title, the calculation steps of the mentioned overall heat transfer coefficient values according to TS825 are mentioned.

Thermal resistance and U-value calculations are important tools to evaluate the performance of different insulation materials and building elements in order to optimize

the thermal insulation of buildings and improve their energy performance.<sup>52</sup> Research on insulation thickness based on this calculation method shows how different insulation strategies can be applied to improve energy performance in buildings located in different climate zones.<sup>53</sup>

In this thesis, the U-value calculations for building roofs are based on the calculation method given by TS825. In this thesis, where U-value calculations were made within the scope of TS825, which was updated during the thesis process, the Overall Heat Transfer coefficient value was calculated for 4 different climate zones for the old TS825, while 6 different U values and related insulation thickness scenarios were created for the current TS825.

In order to understand the U-values, it is necessary to know the thermal resistance factors of the materials. For heat conduction in a single material, the thermal resistance value represents the resistance of the material with unit area to heat transfer. U-value is the mathematical inverse of this thermal resistance. The most basic forms of thermal resistance and U-value for heat conduction in a single material are expressed in Equations 3.1 and 3.2, respectively.

$$R = \frac{L}{k} \quad (3.1)$$

$$U = \frac{1}{R} \quad (3.2)$$

In this equations; R stands for thermal resistance in  $\text{m}^2 \cdot ^\circ\text{C}/\text{W}$ , L stands for material thickness in meters,  $k$  stands for thermal conductivity in  $\text{W}/\text{m} \cdot ^\circ\text{C}$ , U stands for overall heat transfer coefficient in  $\text{W}/\text{m}^2 \cdot ^\circ\text{C}$ .

The calculation of thermal resistance and U-values, which are basically expressed in Equations 3.1 and 3.2, is modified by taking into account the convection resistances in multilayer materials and surfaces. According to this change, the total thermal resistance value is calculated with each material and boundary condition that can create heat transfer resistance. The thermal resistance value shown in Equation 3.1 includes the convective thermal resistance values on the interior and exterior surfaces. The U-value is the

mathematical inverse of the calculated total thermal resistance value. In this context, the formula used in the calculation of the Overall Heat Transfer Coefficient for opaque structural elements is given in Equation 3.3.<sup>15</sup>

$$U = \left[ \frac{1}{h_{in}} + \sum_{i=1}^N \frac{L_i}{k_i} + \frac{L_{ins}}{k_{ins}} + \frac{1}{h_o} \right]^{-1} \quad (3.3)$$

In this equation;  $h_{in}$  is the internal convective heat transfer coefficient in  $W/m^2 \cdot ^\circ C$ ,  $L_i$  is the thickness of material  $i$  (materials from  $i=1$  to  $N$ ) in meters,  $k_i$  is the thermal conductivity of material overlap with  $i$  mesh in  $W/m \cdot ^\circ C$ ,  $L_{ins}$  is the thickness of insulation material in meters,  $k_{ins}$  is the thermal conductivity of insulation material in  $W/m \cdot ^\circ C$  and finally  $h_o$  is the external convective heat transfer coefficient in  $W/m^2 \cdot ^\circ C$ .

Convective heat transfer coefficients on interior and exterior surfaces are defined by TS825. These values may vary according to the velocity of the air, the type of fluid and the properties of the surface material. However, TS825 gives surface heat convection resistance values as constants in order to facilitate the process. In this thesis, these values are used. In this standard, heat convection resistance values for indoor and outdoor surfaces are given as 0.13 and 0.04  $m^2 \cdot ^\circ C/W$ , respectively. In one-dimensional time-dependent heat transfer calculations, these values are used in the form of the  $h$  value, which is mathematically equivalent to the inverse of the convective resistance value. For this reason, internal and external heat convection coefficients are important inputs in the algorithm where the calculation is made. In this program, the heat convection coefficients for indoor and outdoor spaces are assigned as 7.6923 and 25  $W/m^2 \cdot ^\circ C$ , respectively.<sup>15</sup>

### **3.2. One-Dimensional Transient Heat Transfer Problem for Opaque Roof**

In this thesis, heat transfer calculations for opaque roofs were made with the implicit finite difference method. In these roof sections, the materials and the location of the insulation vary according to the roof types. Insulation thicknesses vary for 6 different

cities in accordance with TS825 standards. In transient heat transfer calculations, temperature is also a function of time. Therefore, in such problems, discretization is needed not only in space but also in time. For this discretization, an appropriate time step ( $\Delta t$ ) must be selected. Calculations are made for all times by solving repeatedly for each selected  $\Delta t$  node temperature. In this thesis,  $\Delta t$  is determined as 60 seconds. In addition, the calculations were repeated 1440 times in total, and the temperature distributions in the material during a day, which gives a monthly average, were obtained for different time steps using the monthly averaged Daily data.

In order to write the heat conduction problem correctly, the problem must first be defined correctly. The outdoor temperature data and relative humidity data used in this thesis were provided by the Turkish State Meteorological Service.<sup>13</sup> Radiative sky temperature was calculated based on these values. As seen in Figure 3.1, the radiative sky temperature is an important parameter in Sky Radiation calculations, which is one of the heat transfer parameters.

This figure symbolises the heat transfer factors used in one-dimensional time-dependent heat transfer calculations within the scope of the thesis. In this context, heat is spread through the roof section by conduction. While convective heat transfer, sky radiation and solar radiation calculations are made as the outdoor boundary condition, only the convective heat transfer equation is written as the indoor boundary condition.

$T_{s,o}$  and  $T_{s,L}$  represent the external and internal surface temperature values, respectively. These values are calculated with the code written with the numerical method.  $T_{\infty,o}$  and  $T_{\infty,i}$  represent the temperatures of the air fluid located relatively far from the surface in the external and internal spaces, in short, the ambient temperature of the external and internal spaces. The external temperature is obtained from the data provided by the Meteorological Service and it varies depending on time.<sup>13</sup> In order to keep the indoor temperatures within the thermal comfort limits of residential buildings, they were kept constant at 20°C and 24°C for January and July, respectively.<sup>54</sup> These data are used in the monthly average daily data format during the research process.

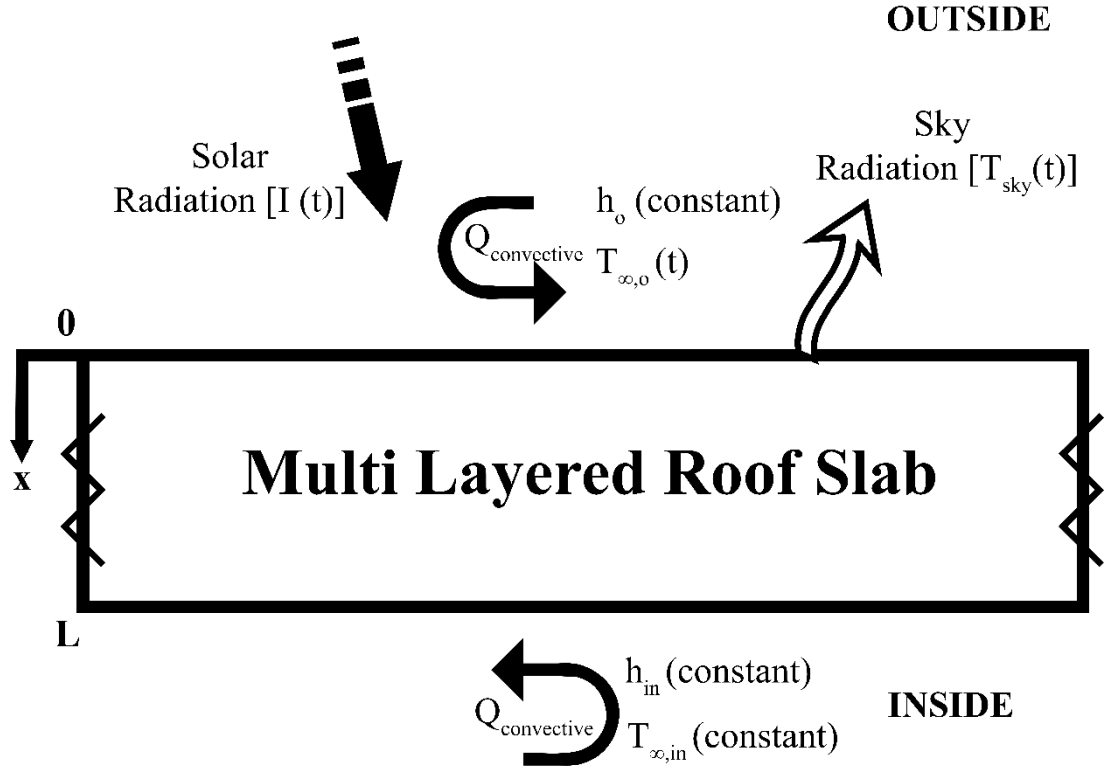


Figure 3.1. One-Dimensional Heat Transfer Through a Roof Slab and Schematic Representation of Heat Transfer Boundary Condition Factors

In the calculations made within the scope of this thesis; for a roof with a one-dimensional heat transfer, multi-layered material arrangement and a total thickness of  $L$ ; it was assumed that each material layer forming the roof is distributed homogeneously within itself and that there is no heat generation along the materials. The time-dependent heat conduction heat transfer formula created with these assumptions is given in Equation 3.4.

$$\rho C_p \frac{\partial T(t, x)}{\partial t} = k \frac{\partial^2 T(t, x)}{\partial x^2} \quad (3.4)$$

In this equation,  $T$  represents temperature in  $^{\circ}\text{C}$ ,  $t$  and  $x$  represents the time and spatial coordinates respectively,  $\rho$  represents the density and  $C_p$  represents the specific heat values.

In this context, the surface boundary conditions and the initial condition are calculated by taking into account the climate properties and material surface properties

with the formulas given in Equations 3.5 and 3.6. According to this formulation, the temperature at point x at the zeroth, or initial time, is also shown in Equation 3.7.

at  $x = 0$

$$-k_0 \frac{\partial T}{\partial x} \Big|_{x=0} = \alpha I(t) + \sigma \varepsilon [T_{sky}^4(t) - T^4(0, t)] + h_o [T_{\infty, o}(t) - T(0, t)] \quad (3.5)$$

at  $x = L$

$$-k_L \frac{\partial T}{\partial x} \Big|_{x=L} = h_i [T(L, t) - T_{\infty, i}(t)] \quad (3.6)$$

at  $t = 0$

$$T(x, 0) = T_{initial} \quad (3.7)$$

According to these formulas,  $k_0$  represents the thermal conductivity value of the material facing the outside environment, and  $k_L$  represents the thermal conductivity value of the material facing the inside environment. While this value is 1.4 for the ceramic tile used in the flat roof type, it is assigned as 0.84 W/m·°C for the roof tile material used in the concrete structure roof type.

The  $\sigma$  symbol represents the Stefan-Boltzmann constant, which is  $5.67 \times 10^{-8}$  W/m<sup>2</sup>K<sup>4</sup>. The  $\varepsilon$  symbol represents the thermal emissivity coefficient of the material. In this thesis, the emissivity value is accepted as 0.9 for the two roof types where one-dimensional time-dependent heat transfer analysis is performed.<sup>40</sup>  $T_{sky}$  represents the radiative temperature of the sky. This temperature value is obtained according to the equations given in Equation 2.1.

In Equation 3.5,  $\alpha$  is the absorption coefficient of the material on the outer surface, which indicates how much of the sunlight in the external environment will be absorbed, and  $I$  is the amount of solar radiation. Thus, by multiplying these two values, the solar radiation gain of the roof structure is obtained. The absorption coefficient for the two roof types examined in this thesis is determined as 0.6.<sup>40</sup> The amount of solar radiation for all cities for which one-dimensional time-dependent heat transfer calculations were made within the scope of the thesis was obtained with the PVGIS system.<sup>38</sup>

In order to make time-dependent calculations with the numerical method, the temperature value must be assigned to the materials along the roof section in question as

the initial condition. The initial temperature along  $x$ , namely the  $T_{\text{initial}}$  value, is expressed with  $T(x,0)$  given in Equation 3.7. This value is assumed to be the average value of the external and internal temperatures for each city and month. With the operation of the program code, all temperature values are obtained for different time steps every 60 seconds using the initial value throughout the day. The temperature distribution values obtained in the last of these process repetitions are the initial values for the next cycle. With this method, the processes are iterated manually until the temperature difference between the new cycle and the previous cycle is less than 0.01 for all meshes, and when this condition is met, the temperature distributions are obtained for different time steps throughout the day.

Within the scope of the thesis, solar radiation data used in one-dimensional time-dependent heat transfer calculations were evaluated based on  $0^\circ$  angle for flat roofs and  $30^\circ$  angle for sloped roofs. In addition to the north, south, east and west orientations with  $30^\circ$  slopes in the Concrete Structure system roof types, flat surface values are also included in the calculations for comparison purposes. Accordingly, the orientation-based solar radiation values obtained for Antalya city for January and July are presented in Figure 3.2 and Figure 3.3, respectively. As seen in Figure 3.2, the  $30^\circ$  south-oriented roof facade receives more than  $600 \text{ W/m}^2$  of solar radiation during the middle of the day in January. According to the July data, this value approaches  $1000 \text{ W/m}^2$  and a similar pattern is observed for the east and west oriented surfaces with a time lag of approximately two hours. The data for the flat surface exhibits a more balanced distribution throughout the day and reaches lower values in the morning and afternoon hours when compared to the sloped surfaces. The solar irradiance data for other cities are presented in Appendix A.

The graphs given in Figures 3.4 and 3.5 show the changes in temperature, relative humidity and radiative sky temperature values calculated accordingly for the months of January and July for Antalya. In the data for January, it is seen that the relative humidity is high (approximately 60-70%) and the temperature is low. This situation also causes the radiative sky temperature to take low values. In July, the increase in temperatures and the fact that the relative humidity remains at lower levels (approximately 40-50%) during the day compared to January, causes the radiative sky temperature to take higher values. These results reveal that relative humidity and temperature changes have a significant effect on the radiative sky temperature. In addition, the significant effect of seasonal

differences on these parameters is striking. Relative humidity, air temperature and calculated sky temperature data for other cities are presented in Appendix B.

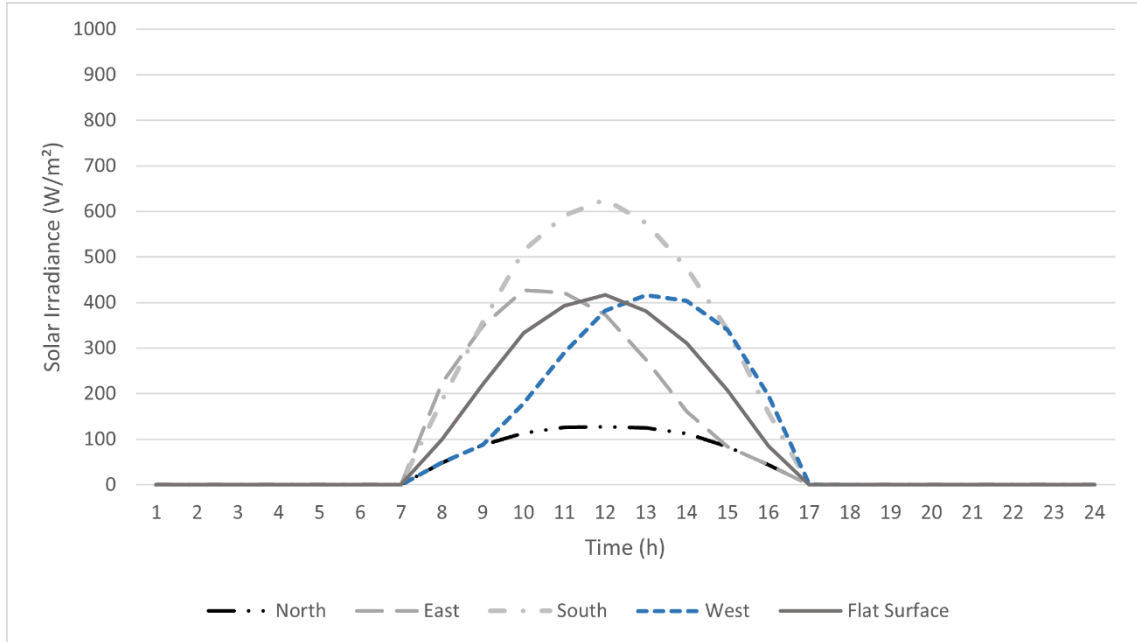


Figure 3.2. Monthly Averaged Daily Data of Solar Radiation in Antalya in January with (Orientations Were Given for 30° Angle)

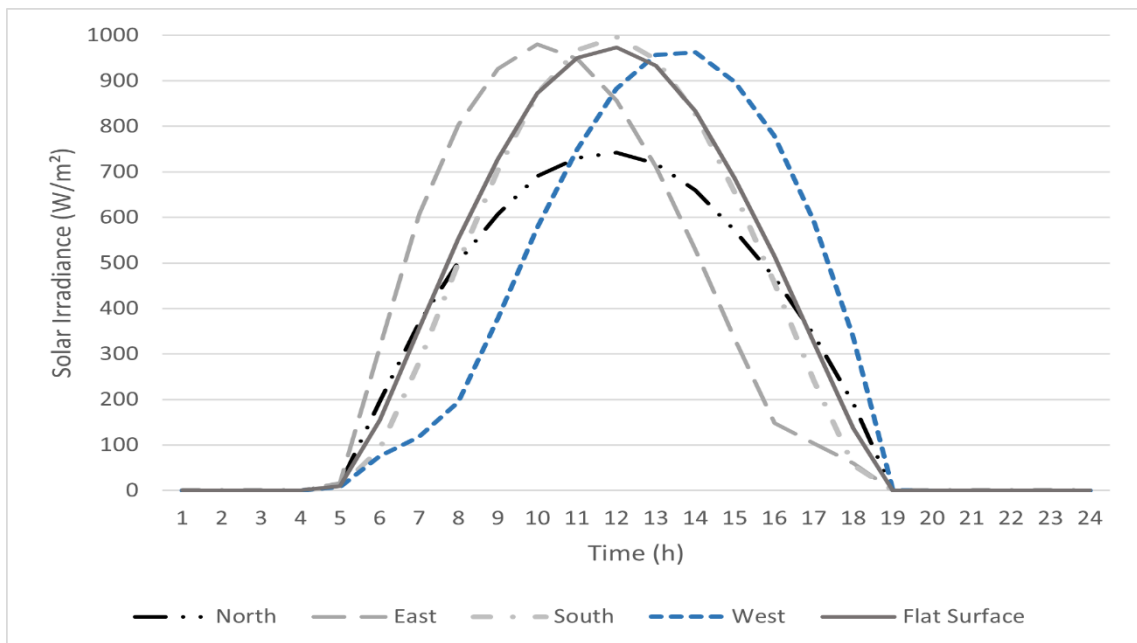


Figure 3.3. Monthly Averaged Daily Data of Solar Radiation in Antalya in July (Orientations Were Given for 30° Angle)

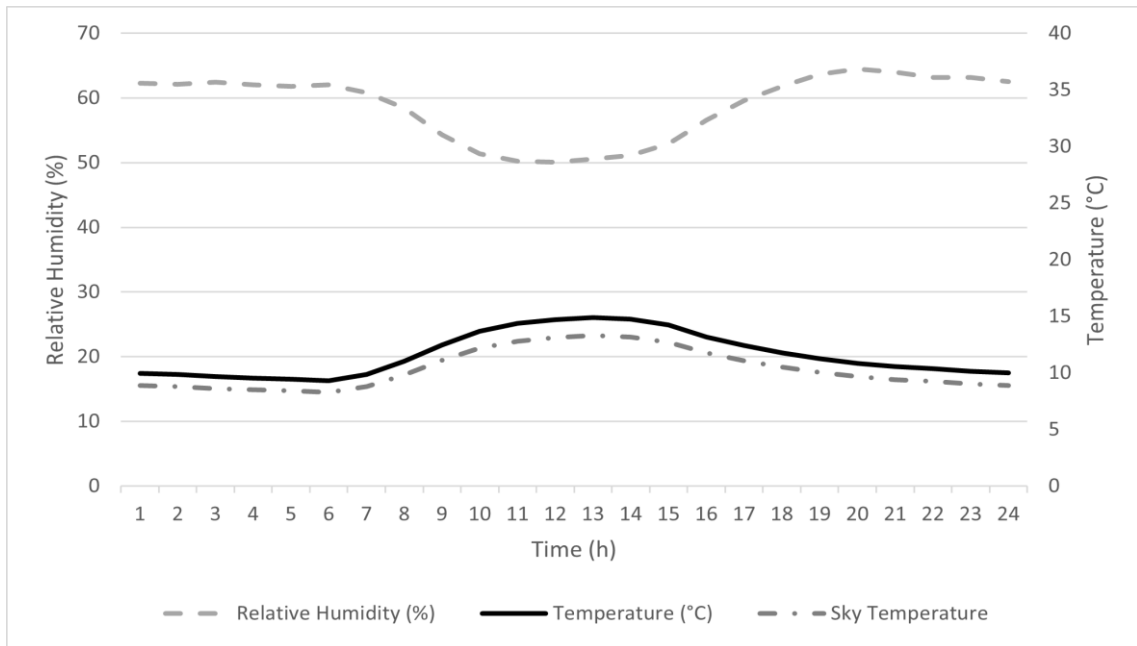


Figure 3.4. Monthly Averaged Daily Data of Radiative Sky Temperature, Which is Calculated based on Relative Humidity and Outside Temperature in Antalya in January

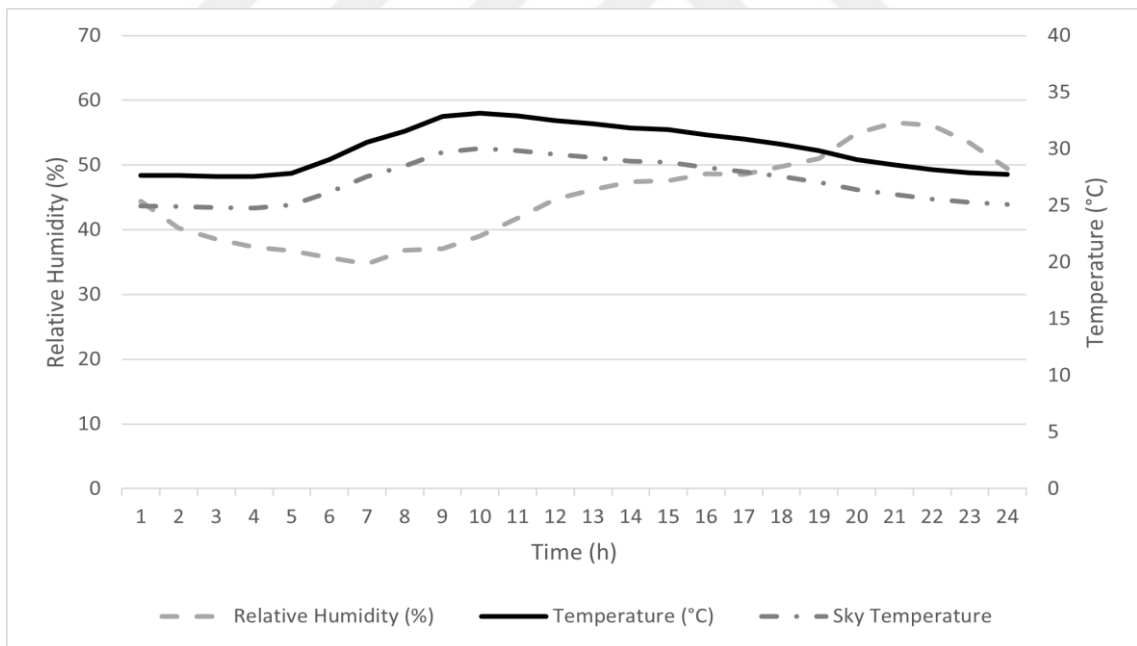


Figure 3.5. Monthly Averaged Daily Data of Radiative Sky Temperature, Which is Calculated based on Relative Humidity and Outside Temperature in Antalya in July

### 3.3. Numerical Analysis of the Problem

Under this subtitle of the thesis, it is explained how to formulate the finite difference method, how to write the partial derivative terms of the finite difference formula with the implicit method, how to write the boundary conditions according to these terms, how to detail the matrix solutions and how to execute the programming language.

When looking at Equation 3.4, the implicit finite difference method representation of the one-dimensional time-dependent heat conduction equation, as defined in the problem, is seen. The numerical approximation solutions of the differential equations found here are shown in Equations 3.8 and 3.9.

$$\frac{\partial T}{\partial t} = \frac{T_j^{i+1} - T_j^i}{\Delta t} \quad (3.8)$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{j+1}^{i+1} - 2T_j^{i+1} + T_{j-1}^{i+1}}{(\Delta x)^2} \quad (3.9)$$

Here, for the letter T, which represents temperature, subscripts represent points separated into meshes, while superscripts correspond to time steps. In this context,  $T_j^i$  represents the temperature at time step i and point j, and  $T_j^{i+1}$  represents the temperature at time step i+1 and point j. The time step formulas here are formulated as;  $t_i = i \cdot \Delta t$  ve  $t_{i+1} = (i+1) \cdot \Delta t$ . In the formula whose second-order differential equivalence is defined in Equation 3.9, j, j+1 and j-1 represent spatial positions. These positions are expressed schematically in Figure 3.6.

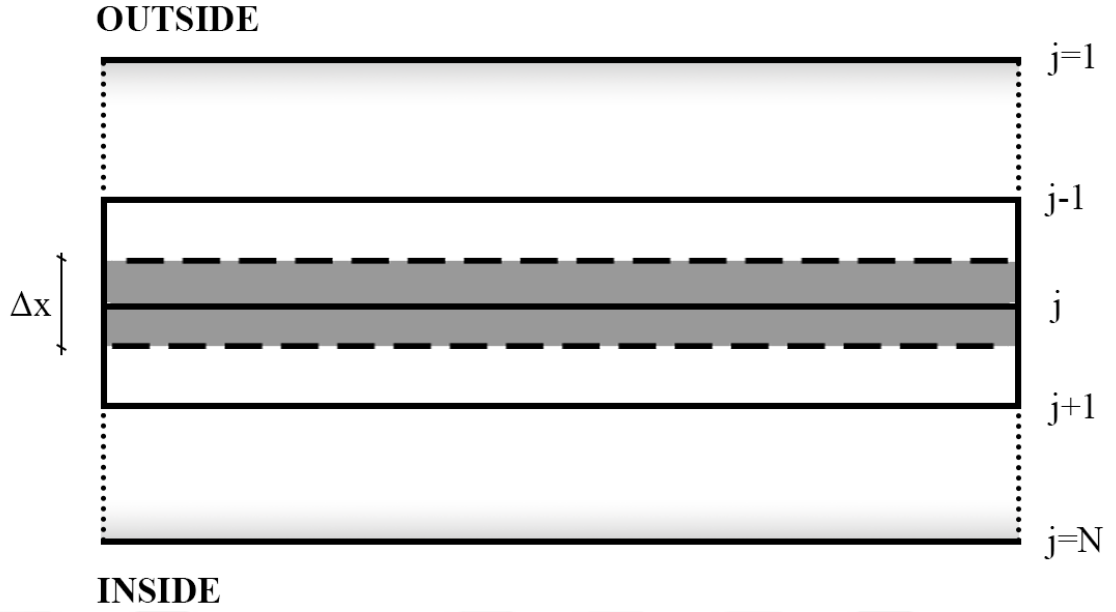


Figure 3.6. The Schematic Presentation of Mesh Nodal Points for One-Dimensional Heat Conduction in Roof Section

According to the Implicit Finite Difference method, the temperature of each point is based on the equality of the sum of the previous and next temperature points.<sup>49</sup> This situation is expressed in Equation 3.9. As a result of the given equations, Equation 3.10 is obtained by writing the equation given in Equation 3.4 as the differential expansions given in Equations 3.8 and 3.9.

$$\frac{T_{j+1}^{i+1} - 2T_j^{i+1} + T_{j-1}^{i+1}}{\Delta x^2} = \frac{\rho C_p}{k} \cdot \frac{T_j^{i+1} - T_j^i}{\Delta t} \quad (3.10)$$

In this equation,  $k/\rho C_p$  is used to express the thermal diffusivity value. This value expresses the rate of heat propagation within the material. In this context, heat conduction occurs more slowly in materials with low diffusivity values, while heat conduction occurs more rapidly in materials with high diffusivity values. When Equation 3.10 is rearranged for each temperature point, Equation 3.11 is obtained.

$$-\frac{1}{\Delta x^2}T_{j-1}^{i+1} + \left(\frac{2}{\Delta x^2} + \frac{\rho C_p}{k\Delta t}\right)T_j^{i+1} - \frac{1}{\Delta x^2}T_{j+1}^{i+1} = \frac{\rho C_p}{k\Delta t}T_j^i \quad (3.11)$$

The temperature values assigned for each mesh point given in this equation constitute an unknown in the equation. In this calculation format, where a separate solution is given for each time step, a tridiagonal matrix system is created to solve the unknowns. In this context, the basic function of the tridiagonal matrix created is given in Equation 3.12.

$$a_j T_{j-1}^{i+1} + b_j T_j^{i+1} + d_j T_{j+1}^{i+1} = c_i \quad (3.12)$$

In this case, the temperature coefficients simplified in Equation 3.12 are as follows:

$$a_j = +\frac{1}{\Delta x^2} \quad (3.12.1)$$

$$b_j = -\left(\frac{2}{\Delta x^2} + \frac{\rho C_p}{k\Delta t}\right) \quad (3.12.2)$$

$$d_j = +\frac{1}{\Delta x^2} \quad (3.12.3)$$

$$c_j = -\frac{\rho C_p}{k\Delta t}T_j^i \quad (3.12.4)$$

The equation system formed by expressing these differential equations for each mesh point becomes a linear equation set containing all temperature unknowns. This linear system can be arranged in a convenient matrix form. In this context, the temperatures determined for the interior points in the solution area are defined as  $T_j^{i+1}$  unknowns and the system formed for each time step is expressed with a tridiagonal matrix structure as in Figure 3.7.<sup>55</sup>

$$\begin{bmatrix}
b_1 & d_1 & 0 & 0 & \dots & 0 & 0 & 0 \\
a_2 & b_2 & d_2 & 0 & 0 & \dots & 0 & 0 \\
0 & a_3 & b_3 & d_3 & 0 & 0 & \dots & 0 \\
\vdots & & \ddots & \ddots & \ddots & & & \vdots \\
0 & 0 & 0 & a_j & b_j & d_j & 0 & 0 \\
\vdots & & & \ddots & \ddots & \ddots & & \vdots \\
0 & & \dots & & 0 & a_{n-2} & b_{n-2} & d_{n-2} \\
0 & 0 & & \dots & & 0 & a_{n-1} & b_{n-1} \\
0 & 0 & 0 & & \dots & & 0 & a_n
\end{bmatrix}^{i+1} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_j \\ \vdots \\ T_{n-2} \\ T_{n-1} \\ T_n \end{bmatrix}^{i+1} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_j \\ \vdots \\ C_{n-2} \\ C_{n-1} \\ C_n \end{bmatrix}^i$$

Figure 3.7. Schematic Representation of Thomas Tridiagonal Matrix Algorithm

The equations in the Tridiagonal matrix system schematized in this figure are solved using the Thomas Tridiagonal Matrix Algorithm (TDMA). This method is a simplified version of the classical Gauss Elimination method that can be applied to systems with elements on only three bands. In this algorithm, first, new coefficients are obtained, and then the temperature values are calculated with back substitution. In order to apply Back Substitution, the  $b_j$  and  $c_j$  values in the matrix must first be known. These values are obtained by sequentially solving the equations in Equations 3.13 and 3.14.

$$b_j = b_j - \frac{a_j}{b_{j-1}} \cdot d_{j-1} \quad j = 2, 3, 4, \dots, n \quad (3.13)$$

$$c_j = c_j - \frac{a_j}{b_{j-1}} \cdot c_{j-1} \quad j = 2, 3, 4, \dots, n \quad (3.14)$$

In these equations, the positional variable  $j$  varies sequentially between 2 and  $n$ . The unknowns constituting the first row of the matrix are filled with initial temperature values. The remaining unknown temperature values are estimated with the Back Substitution equations in Equations 3.15 and 3.16.

$$T_n = \frac{c_n}{d_n} \quad (3.15)$$

$$T_j = \frac{c_j - a_j \cdot T_{j+1}}{d_j} \quad i = n-1, n-2, n-3, \dots, 3, 2, 1 \quad (3.16)$$

This direct solution method was used to solve the problem, reduced to the tridiagonal matrix system that arose in the calculation of one-dimensional transient heat transfer defined using the modified Gauss Elimination procedure. The one-dimensional transient heat conduction problem defined for the roof section can be solved by the TDMA method using the initial and boundary conditions. The boundary conditions for this solution are mentioned in the subheadings.

### 3.3.1. Outside Boundary Condition

In this thesis, the materials selected for one-dimensional transient heat transfer calculations are opaque. In this context, the boundary condition for the outer surface of the opaque roof is schematically expressed in Figure 3.8.

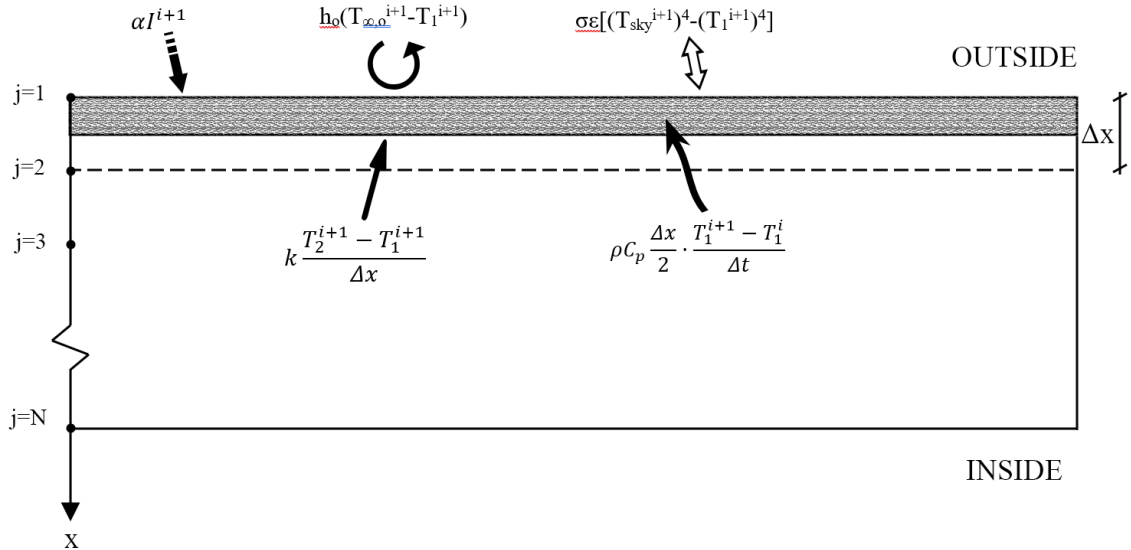


Figure 3.8. Schematic Presentation of Outside Boundary Condition and Heat Transfer Equilibrium of a Compact Roof Section's Volume Element for Finite Difference Formulation in One-Dimensional Transient Heat Transfer

The equation obtained according to this figure is given in Equation 3.17.

$$\begin{aligned} \alpha I^{i+1} + h_o(T_{\infty,o}^{i+1} - T_1^{i+1}) + \sigma \varepsilon \left[ (T_{sky}^{i+1})^4 - (T_1^{i+1})^4 \right] \\ + k \frac{T_2^{i+1} - T_1^{i+1}}{\Delta x} = \rho C_p \frac{\Delta x}{2} \cdot \frac{T_1^{i+1} - T_1^i}{\Delta t} \end{aligned} \quad (3.17)$$

In this equation,  $T_1$  represents the outer surface temperature, and  $T_{sky}$  represents the calculated sky temperature. While temperature values are expressed in Celsius in all equations, in the equation where sky radiation calculations are made, temperature values taken to the power of 4 are included in the calculation within Kelvin.

This external boundary condition is modelled by taking into account the external temperature, the sky temperature, and the convective and radiative heat exchanges between the external surface and the environment. This equation ensures that the temperature distribution on the external surface is accurately determined at each time step.

### 3.3.2. Inside Boundary Condition

The inner boundary condition defines the heat exchange between the inner surface of the opaque roof and the inner environment. In this thesis, it is assumed that the inner temperature remains constant over time. Therefore, only the convective heat transfer between the inner air and the inner surface is taken into account. Thermal radiation between the inner surfaces is neglected. In Figure 3.9, the inner surface boundary condition and the schematic representation of the parameters affecting this condition are presented.

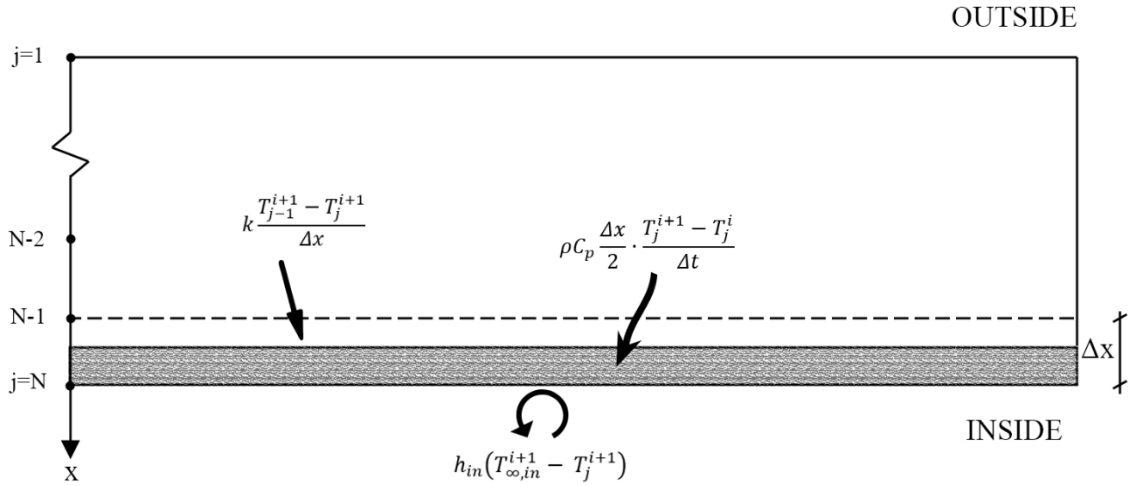


Figure 3.9. Schematic Presentation of Inside Boundary Condition and Heat Transfer Equilibrium of a Compact Roof Section's Volume Element for Finite Difference Formulation in One-Dimensional Transient Heat Transfer

The equation obtained according to this figure is given in Equation 3.18.

$$h_{in}(T_{\infty,in}^{i+1} - T_L^{i+1}) + k \frac{T_{N-1}^{i+1} - T_L^{i+1}}{\Delta x} = \rho C_p \frac{\Delta x}{2} \cdot \frac{T_L^{i+1} - T_L^i}{\Delta t} \quad (3.18)$$

As schematized in Figure 3.9, the indoor surface temperature is expressed in the equation as  $T_N = T_L$ . This boundary condition is solved at each time step in order to determine the temperature change on the indoor surface and is completed with the relation expressing the convective heat transfer between the indoor environment and the surface. The equation is written according to energy balances and includes conduction, storage and convective heat transfer components.

### 3.3.3. Interface Boundary Condition

Roof opaque structural elements are generally composite materials consisting of layers with different thermophysical properties. Therefore, special boundary conditions must be defined in terms of heat transfer at the intersection points of the layers. In

particular, special formulations based on the principle of energy conservation are needed for these transition regions in time-dependent one-dimensional heat transfer problems. Figure 3.10 schematizes the interface boundary condition of roofs where one-dimensional time-dependent heat transfer calculations are made with the implicit finite difference method within the scope of the thesis.

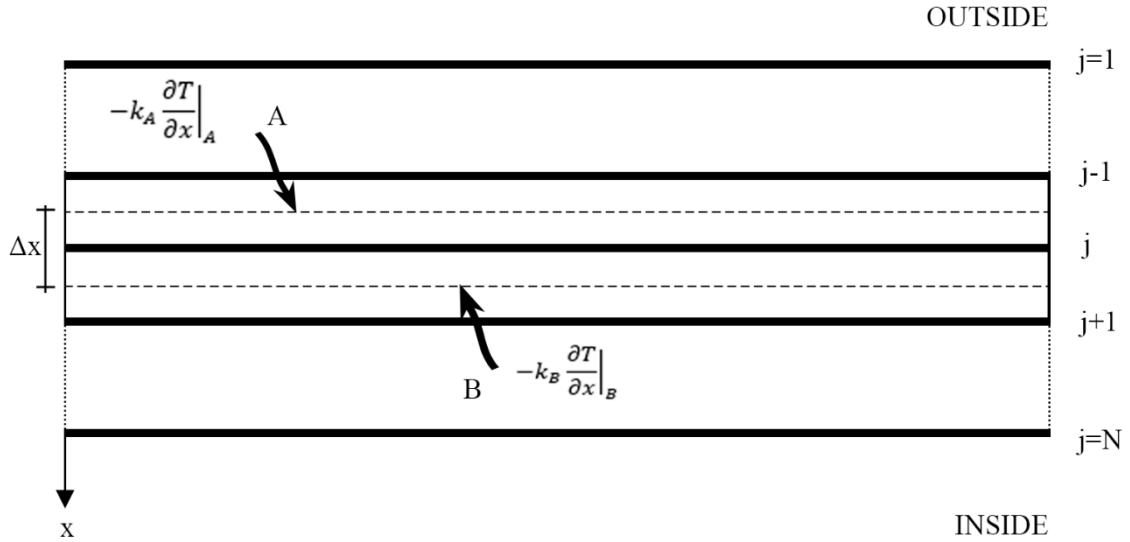


Figure 3.10. Schematic Presentation of Interface Boundary Condition and Heat Transfer Equilibrium of a Compact Roof Section's Volume Element for Finite Difference Formulation in One-Dimensional Transient Heat Transfer

There are different material intersections along the roof section. For this reason, the energy balance formula for each intersection point is given in Equation 3.19.

$$\left( k_A \frac{T_{j-1}^{i+1} - T_j^{i+1}}{\Delta x} \right) + \left( k_B \frac{T_{j+1}^{i+1} - T_j^{i+1}}{\Delta x} \right) = 0 \quad (3.19)$$

The energy balance equation for the Interface Boundary must be discretised for the matrix system. In this context, Equation 3.19 can be modified as Equation 3.20.

$$-T_{j-1}^{i+1} + \left(1 + \frac{k_B}{k_A}\right) T_j^{i+1} - \frac{k_B}{k_A} T_{j+1}^{i+1} = 0 \quad (3.20)$$

With the equation given in this equation, the temperature at the interface points of different materials along the roof section is calculated depending on time.

### 3.4. Programming Language

In this thesis, one-dimensional transient heat transfer analysis was calculated with the help of coding written in the Microsoft Visual Basic 6.0 program with the implicit finite difference method. This program can perform event-based and object-oriented programming and is highly preferred in physical calculations such as one-dimensional transient heat transfer calculations.<sup>56</sup> In addition, Microsoft Visual Basic 6.0 stands out with its ease of graphical user interface development, its accessibility to users with basic programming knowledge, and the flexibility it offers in computational engineering applications. For this reason, it is used as an effective tool in educational environments and engineering analyses for understanding and applying heat transfer principles.<sup>57</sup>

All mathematical calculations made within the scope of the thesis were carried out through the coding created in this program. In this context, a general flowchart about the coding is given in Figure 3.11 regarding the creation and operation of the program.

In the flowchart shown in Figure 3.11, it is explained step by step how the Visual Basic code solves the one-dimensional time-dependent heat transfer problem with the numerical method. In this coding, multi-numbered loop operations solved with the implicit finite difference method are performed. The flowchart steps to be explained below are numbered with Roman numerals on the right side of Figure 3.11.

In this context, in step I, the locations of the .txt format files that the program should read as input are defined.

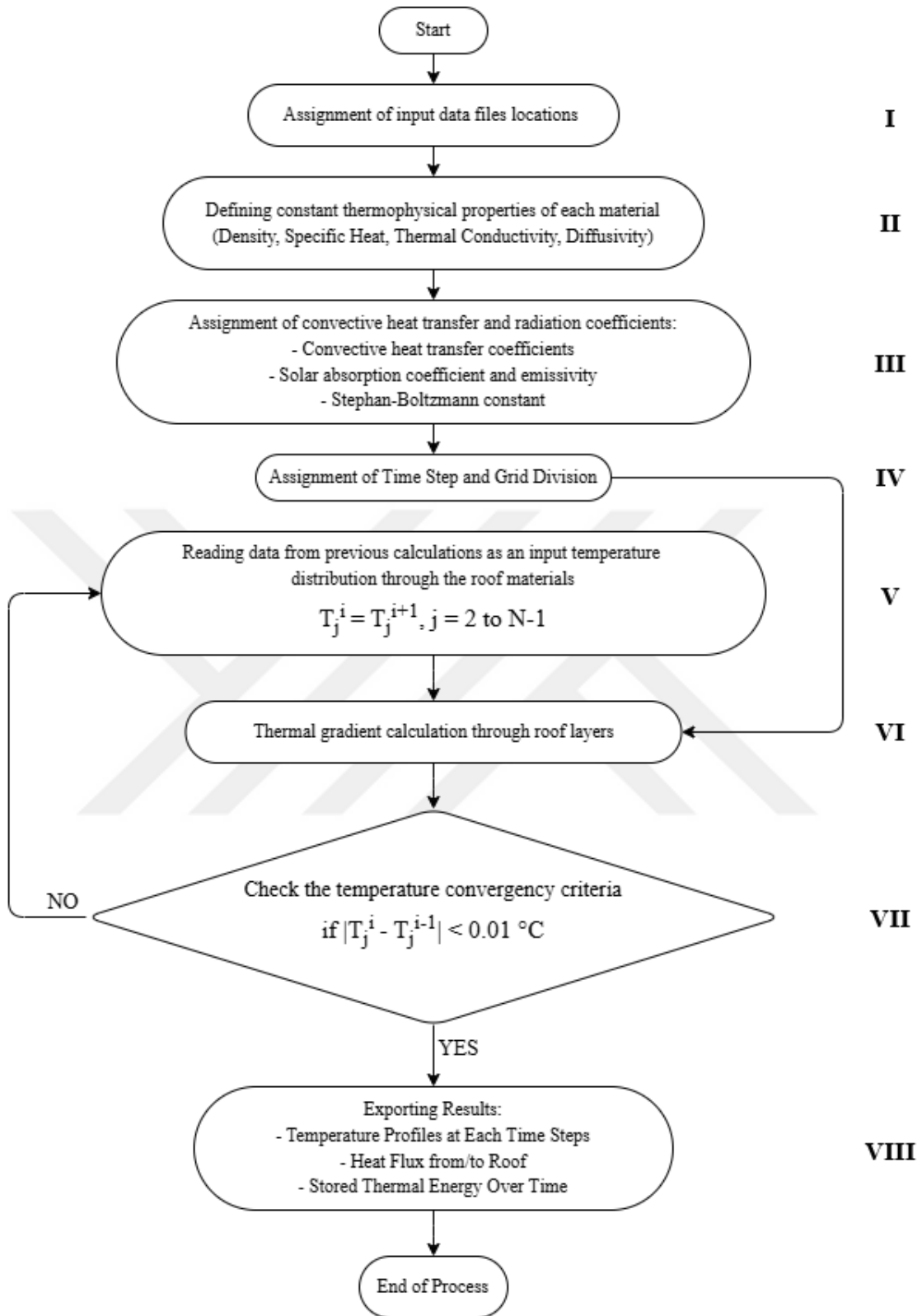


Figure 3.11. Schematic Design of the Computational Flow in Visual Basic 6.0

In step II, thermal conductivity and thermal diffusivity values of the materials in the roof composition are inserted. Thermal diffusivity ( $k/\rho \cdot C_p$ ) value is calculated with thermal conductivity ( $k$ ), density ( $\rho$ ) and specific heat under constant pressure ( $C_p$ ) values and the calculated numerical value is inserted into the program as constant values.

In step III, the internal ( $h_i$ ) and external ( $h_o$ ) convective heat transfer coefficients were submitted as 7.6923 and 25 W/m<sup>2</sup>·K, respectively. In addition, the solar absorptivity value of 0.6 and the emissivity value of 0.9 were assigned as constant for all roof types within the same group. Finally, the Stefan-Boltzmann constant ( $\sigma$ ), which is important for solar radiation calculations, was assigned as  $5.67 \times 10^{-8}$  W/m<sup>2</sup>·K<sup>4</sup>.

In step IV, each mesh interval is defined. Since the thickness changes in each roof type, the mesh intervals of these roofs are mathematically formulated for each roof. Thus, the mesh interval is assigned as 0.001 meters. Each time step ( $\Delta t$ ) is also defined within this group. Time steps limited to time steps 1 to M are defined in total: 1 day / 1 minute = 1440 time intervals to form a daily cycle with 60-second intervals.

In step V, the initial temperature values for each internal node to be analysed in the roof layers are defined based on the results obtained from the previous time step. This method is of critical importance for ensuring temporal continuity in time-dependent heat conduction problems. Mathematically, this process is defined by the expression  $T_j^i = T_j^{i+1}$ , where the internal node points between  $j = 2$  and  $N-1$  are covered. Thanks to this approach, it is possible to obtain an accurate and stable temperature field at each time step.

In step VI, the temperature differences occurring in each layer of the roof structure elements are taken into account, and the heat gradient between the relevant layers is calculated. The heat gradient is defined as proportional to the temperature change according to Fourier's heat conduction law and determines the direction and intensity of the heat flow between the surfaces. This calculation constitutes the basic data source for the temperature update and balancing process to be carried out in the next step.

For this reason, in step VII, in order to ensure the accuracy and stability of the numerical solution, the temperature convergence criterion is manually checked at the end of each time step. For this purpose, the temperature difference in two consecutive iterations is calculated for each internal node point, and it is evaluated whether this difference falls below the specified tolerance value of 0.01 °C. When this value is

exceeded, the temperature distribution values along the roof section calculated in the last cycle are assigned as the new starting value, and this process is included in the cycle. When a value below the tolerance value is obtained, it is passed to the next step.

In step VIII, when the convergence condition is met, the solution results for the relevant time step are exported. These results include the temperature profiles obtained for each time step, the heat flux values from the outer surface and the inner surface of the roof, and the amount of accumulated thermal energy over time calculated based on these values. These data are used both to evaluate the energy performance of the system and to perform comparative analyses of different roof types. In this context, numerical data is obtained and becomes suitable for analysis. The results obtained from the quantitative basis of the heat conduction analysis carried out within the scope of the thesis.

### **3.5. Assumptions**

Under this title of the thesis, all the facts assumed for making one-dimensional transient heat transfer calculations are mentioned. These assumptions are important for each step of the heat transfer problem, and the calculation method is created accordingly.

- In this thesis, heat transfer is assumed to be one-dimensional for the roof types for which time-dependent heat transfer calculations are made. In this context, the heat transfer of the roofs in question with different structural elements, such as walls or floors, is not calculated.
- The roofs are assumed to be perfectly opaque for both roof types. It is assumed that there is no air flow across the roof section, assuming that the materials have a 100% leak-proof ratio.
- Each roof material is assumed to be homogeneously distributed within the material.
- It is assumed that there is no change in the thermal properties of the materials depending on the temperature gradient occurring in the roof section.

- In this thesis, water vapour diffusion was ignored while performing one-dimensional transient heat transfer calculations.
- The convective heat transfer coefficient is assumed to be constant for each case, assuming that the wind speed is constant in the outdoor and indoor environments. In this context, while  $h_o$  is 25 for the outdoor surface,  $h_i$  is 7.6923 W/m<sup>2</sup>·K for the indoor surface. This assumption is based on the TS825 standard.<sup>14</sup>
- The solar radiation values obtained from the PVGIS system<sup>38</sup> calculate the radiation values on the horizontal plane. For this reason, solar radiation values on roof types with an angle of 30° are calculated by linear interpolation, which is done automatically by the system.
- Indoor ambient temperatures are assumed to be constant at 24°C for July and 20°C for January.
- Data for each month was given as input to the process in a monthly averaged daily data format, interpolated at one-minute intervals. In this way, daily analysis was performed.
- The contact resistance effects in the tangential direction that may occur at the intersection points of different materials encountered along the roof section are not taken into account.
- The growth or decrease of an error occurring in a loop in the code over time depends on the number of time steps that have passed since the error occurred. In this process, the behaviour of the error grows or shrinks exponentially as much as the relevant time step number of the growth factor. Therefore, the error can either increase and create serious effects on the solution or fade away over time and lose its effect. It is assumed that the errors in question are reset in each manual loop. Thus, the error margin in the heat transfer problem solved by the implicit finite difference method is considerably reduced.

## **CHAPTER 4**

### **CASE STUDY DEFINITION AND PARAMETERS**

Heat transfer through building roofs under different climatic conditions plays a critical role in terms of both comfort and energy consumption. In this context, under this chapter of the thesis, the climatic data of the cities selected for comfort conditions, the roof types evaluated within the scope of the thesis and the related building materials are detailed. In this chapter, the case study that forms the basis of one-dimensional time-dependent heat transfer analysis is comprehensively defined. The selected cities are evaluated in terms of their climatic diversity, and the roof types and material properties are discussed in terms of energy performance.

#### **4.1. City Selection Parameters and Climatic Properties of Selected Cities**

In studies where heat transfer calculations will be made in buildings, it is important to select the cities where these studies will be conducted. In this way, heat losses and gains can be compared accurately between different cities. Each comparison contributes to making important design decisions in order to increase building energy performance and improve thermal comfort.<sup>58</sup>

In this thesis, the TS825 standard has been taken as a guide in defining the U-values and determining cities with different climates. The TS825 standard divides Türkiye into only 4 different degree-day regions in thermal insulation calculations in buildings and uses fixed climatic parameters for these regions. The map showing the climate classification in question is given in Figure 4.1. In the new arrangement of TS825, the number of regions has been increased to 6, as seen in Figure 4.2. However, this approach, together with temperature and solar radiation values based on monthly averages, leads to cities with different geographical and meteorological characteristics being evaluated

within the same region. This causes local conditions to be ignored. For example, there are significant differences in sunshine duration, solar radiation gain, humidity and outdoor temperature profiles between a coastal city and a high-altitude inland city in the same climate zone. In the tables presented by TS825, only the values of fixed solar radiation according to the four main directions are given as the thermal load passing through semi-transparent windows into the indoor environment. Parameters such as the effect of solar radiation on opaque surfaces, surface slope and local orientation are ignored.<sup>59</sup> On the other hand, in some studies where city-based climate data are taken into consideration in order to ensure that the results are more reliable, as in this thesis, data such as design temperatures and solar radiation are calculated in long-term meteorological measurements and evaluated separately for each province and time-dependent analyses are evaluated.<sup>60</sup> In these studies, it is emphasized that regional and city-based U-value maps should be created in accordance with European practices in terms of energy efficiency.<sup>61</sup> In this context, instead of the fixed and regional approach of TS825, choosing 6 cities with different climatic characteristics was preferred as a more suitable method both to perform more detailed analysis and in terms of energy efficiency targets.

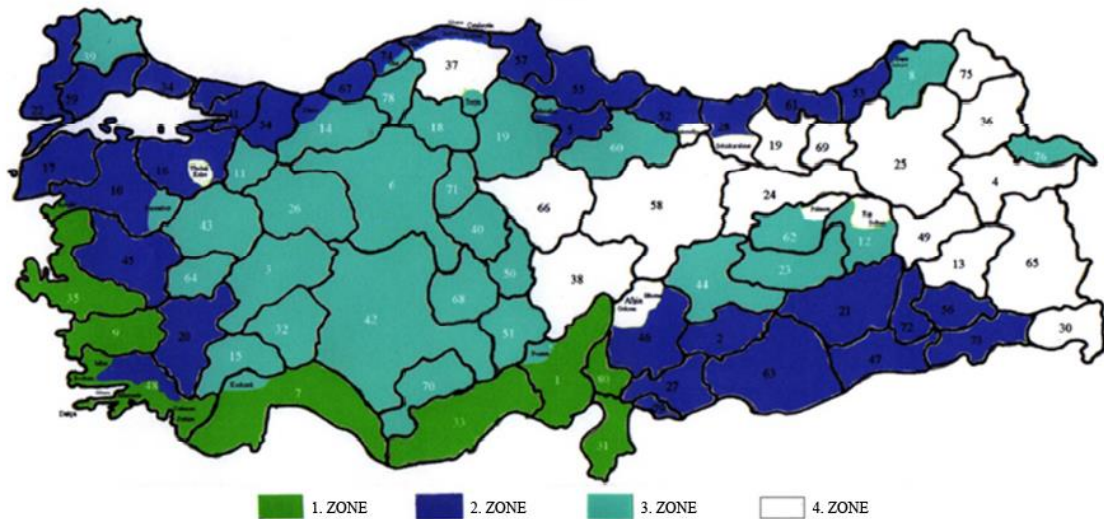


Figure 4.1. The Map of Old TS825 Climatic Classification in Türkiye  
(Source: Turkish State Meteorological Services)

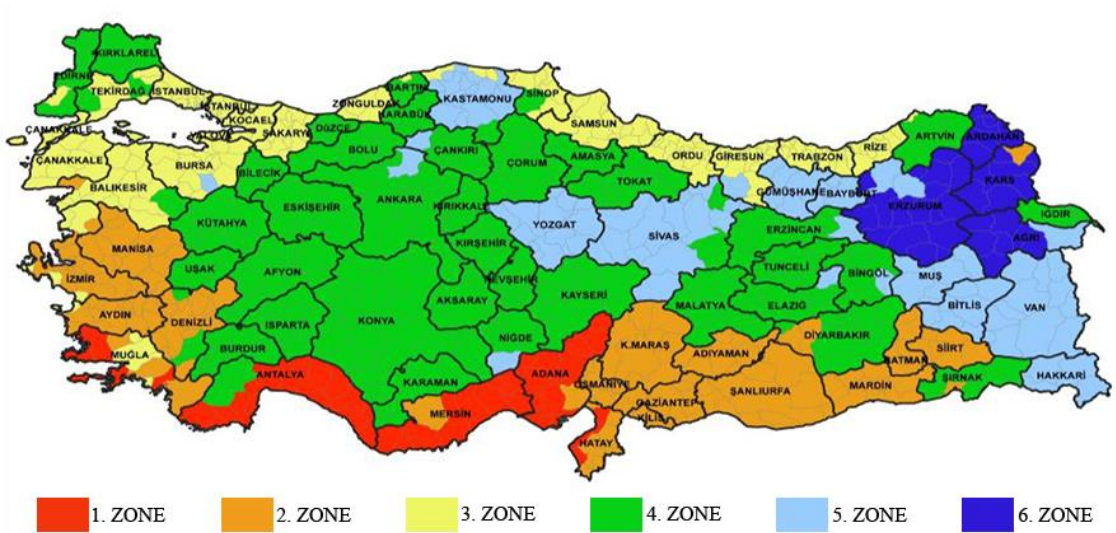


Figure 4.2. The Map of Current TS825 Climatic Classification in Türkiye  
(Source: Turkish State Meteorological Services)

The only difference between the old TS825 and the current TS825 standard is not the number of climate zones they have divided the country into. According to the old TS825 standards, only heating load analysis was performed for newly constructed or already constructed buildings. In contrast to this situation, the updated TS825 has brought the requirement to perform the necessary analyses for both heating and cooling loads of the buildings. In this thesis study, both heating and cooling load calculations were made and compliance with the current TS825 was achieved.

Table 4.1 shows that when selecting the cities for heat transfer calculations within the scope of old TS825, the number of cities in the 2nd and 4th regions is two each. It is clearly seen that the climate zones of these cities are separated in the current TS825. In this context; Antalya city, which was in the 1st Region, remains as the 1st Region, Istanbul city, which was in the 2nd Region, has been updated as the 3rd Region, Şanlıurfa city, which was in the 2nd Region, has remained as the 2nd Region, Ankara city, which was in the 3rd Region, has been updated as the 4th Region, Sivas city, which was in the 4th Region, has been updated as the 5th Region and Ardahan city, which was in the 4th Region, has been updated as the 6th Region.

Table 4.1. Comparative Table of Selected Cities Depending on Regulations

| Provinces | Climatic Regions Based on Regulations |                        |
|-----------|---------------------------------------|------------------------|
|           | Old TS825 Standart                    | Current TS825 Standart |
| Antalya   | 1                                     | 1                      |
| Şanlıurfa | 2                                     | 2                      |
| İstanbul  | 2                                     | 3                      |
| Ankara    | 3                                     | 4                      |
| Sivas     | 4                                     | 5                      |
| Ardahan   | 4                                     | 6                      |

Within the scope of this thesis, it is not only the TS825 evaluation that affects the city selection. There are also different parameters: Köppen-Trewartha climate classification, annual average outdoor temperature values, HDD and CDD values and Solar radiation maps. As a result of the parameters evaluated separately, 6 cities corresponding to different climate conditions were selected from 81 cities in Türkiye.

#### 4.1.1. Köppen-Trewartha Climatic Classifications

Climate classifications are the fundamental tools that enable climate data to be defined and understood within an orderly system. These classifications enable the development of strategies suitable for environmental conditions in many areas such as agriculture, ecology, urban planning and especially building design. When considered at the building scale, climate types are the basic inputs of many decisions such as thermal insulation, facade design, passive methods, natural ventilation and energy efficiency.<sup>62</sup> Türkiye is a country that exhibits significant climatic differences even at short distances due to its geographical diversity. This situation necessitates the consideration of local climate data in terms of building design and energy performance. However, the old TS825 standard divides the country into only four degree-day zones and makes a generalization that ignores microclimatic differences in different cities. Therefore, within the scope of the thesis, the Köppen-Trewartha climate classification<sup>63</sup> prepared by the Turkish State Meteorological Service (TSMS), which is a more detailed and representative approach, and city selections were made in line with the research conducted on this subject. This

classification divides Türkiye into five main climate classes based on the annual distribution of temperature and precipitation and these are divided into various subtypes. It defines the climate type and seasonal characteristics for each city in detail. This method allows for much more accurate and locally based solutions in architectural decisions such as building envelope design, insulation thickness, and orientation. In this context, climatic diversity has been analyzed more realistically by selecting six different city-based samples. Accordingly, data that will directly affect building energy performance has been used.

The climate classifications mentioned in this thesis have been an important parameter in city selection. For this reason, knowing the characteristics of the climate classes seen in Türkiye is important for both energy performance improvements and research to be conducted. In this context, the climate classes seen in Türkiye have been examined. The Köppen-Trewartha climate classes corresponding to the cities selected in the thesis research are stated with their explanations in Table.4.2.

Table 4.2. Climatic Characteristics of the Selected Cities Based on Köppen-Trewartha Climatic Classification

| <b>Provinces</b> | <b>Köppen-Trewartha Climate</b> | <b>Climatic Characteristics in Summary</b> |
|------------------|---------------------------------|--------------------------------------------|
| <b>Antalya</b>   | Cshk                            | Very Hot Summers, Cool Winters             |
| <b>Şanlıurfa</b> | Cshk                            | Very Hot Summers, Cool Winters             |
| <b>İstanbul</b>  | Csak                            | Hot Summers, Cool Winters                  |
| <b>Ankara</b>    | Dcak                            | Hot Summers, Cool Winters                  |
| <b>Sivas</b>     | Dcbo                            | Warm Summers, Cold Winters                 |
| <b>Ardahan</b>   | Dclc                            | Mild Summers, Very Cold Winters            |

Köppen-trewartha climate classification defines 6 main climate groups. This classification divides the climates into subgroups to make them more detailed. It divides these six main groups into different subgroups with humidity rates and universal temperature scale index in climate classifications. The code letters that represent each main group and subgroup are arranged in a certain order to make the distinctions easier.

According to the coding logic, the first letter represents one of the main climate classes. These classes, coded alphabetically as A, B, C, D, E and F, represent tropical,

arid, subtropical, temperate, northern and polar climates, respectively. The second letter of the code represents the sub-groups of the main climate groups. In subtropical climates starting with the 'c' code, the 's' code represents the subtropical dry summer climate sub-group. In temperate climates starting with the "c" code, the 'c' code represents the temperate continental climate. In this context, Table 4.2 shows that the six cities selected for time-dependent one-dimensional heat transfer calculations belong to two main climate groups and the same sub-groups of these main groups. However, these cities are distinguished from each other by the universal temperature scale index abbreviations that form the last two letters of the code. This index indicates the average monthly temperature values for summer and winter months, respectively, with the third and fourth letters. The h code denotes the range of 28°C to 34.9°C as very hot, the a code denotes the range of 23°C to 27.9°C as hot, the b code 18°C to 22.9°C as mild, the l code as 10°C to 17.9°C as temperate, the k code as 0.1°C to 9.9°C as cool, and finally the o code as -9.9°C to 0°C as cold.

As shown in Table 4.2, the six cities selected for heat transfer calculations are coded with abbreviations representing different climatic characteristics. These cities exhibit similar climatic characteristics, but their microclimatic differences are important in their selection for heat transfer calculations in this thesis.

#### **4.1.1.1. Semi-Arid Steppe Climate Region**

Semi-Arid Steppe climate is a type of climate with low annual rainfall. This climate is defined as a transitional climate because it is between arid and humid climates. It makes continental effects felt not only seasonal but also because of the high daily temperature differences. In the regions where this climate is seen, where there is not enough water for plants to grow, there are generally grasses and shrubs. With climate change, negative effects such as increasing temperature, irregular rainfall and decrease in water resources are observed. In the face of this situation, adaptation strategies such as sustainable land management should be developed. These strategies should cover not only building classes but also sectors such as infrastructure and superstructure. These multi-dimensional characteristics of the semi-arid steppe climate require a comprehensive

assessment in terms of sustainable management of natural systems and making them resistant to climate change.<sup>64</sup>

According to the values shown by the Köppen-Trewartha climate classification studies, this climate class is the rarest climate class seen in Türkiye. Only 2.38% of Türkiye is included in this climate class in terms of surface area. In the study, only Ağrı province is fully included in this climate class.<sup>63</sup>

#### **4.1.1.2. Humid Subtropical Climate Region**

Humid Subtropical climates are a climate class included in the Köppen and Köppen-Trewartha climate classifications. In this climate, summer months are hot and humid, while winter months are slightly cold. While temperatures are above normal 30 °C in summer months, temperatures rarely drop below freezing in winter months. Convective storms and summer rains caused by tropical cyclones are also seen in this climate region in summer months. In these regions, due to the humidity reaching saturation, vapor diffusion problems and related conditions that negatively affect thermal comfort in interior spaces are experienced. Unlike other tropical climates, humid subtropical climate regions can show their characteristic features in all four seasons. This climate type is generally located between 25° and 40° latitudes of the continents.<sup>65</sup>

7.94% of Türkiye's surface area includes humid subtropical climate characteristics. This climate type is frequently seen in cities neighbouring the Black Sea in Türkiye.<sup>63</sup> Ordu, Samsun, Rize, Trabzon and Sinop can be given as examples of these cities, the majority of which fall into the second region in the old TS825 standard.

#### **4.1.1.3. Dry Subtropical Summer Climate Region**

The Dry Subtropical Summer climate is a type of climate generally referred to as the Mediterranean climate. In these climate zones, summer months are very hot, dry and rainless. Rainfall in the summer months is prevented due to the dominance of subtropical high-pressure systems. In the winter months, significant amounts of precipitation are

generally received due to air currents coming from the poles and mid-latitudes. These months with precipitation are described as warm and cold. In this climate class, where precipitation occurs mostly in the winter months, the seasons are sharply separated from each other in terms of their characteristics. Despite receiving precipitation in the winter months, regions exhibiting these climate characteristics are at risk of drought in the summer months. In these regions, the temperature is above 30 °C in the summer months and rarely drops below freezing in the winter months. Dry subtropical summer climate characteristics are generally encountered around the Mediterranean and on other continents with similar latitudes.<sup>66</sup>

30.95% of Türkiye's surface area includes Mediterranean climate characteristics. These climate characteristics are frequently seen in the Marmara, Aegean and Mediterranean regions of Türkiye. Examples of these regions are Çanakkale, İzmir, Aydın, Muğla, Antalya, Adana, Osmaniye and Hatay.<sup>63</sup> The city of Antalya, which was chosen for calculations in this thesis, is also a city with these climate characteristics. However, it should be noted that more than one parameter was considered in the selection of the city and that only the Köppen-Trewartha climate classification was not followed.

#### **4.1.1.4. Temperate Continental Climate Region**

It is the most common climate type in Türkiye and is characterised by high seasonal temperature differences. This climate type is generally seen in inland areas far from the sea, where oceanic or maritime influences are not very noticeable. As a result, the seasonal temperature range is quite wide. In summer, temperatures are above 10 °C, but the rate of increase varies from region to region. Similarly, in winter, temperatures fall below freezing. As a result, there is a permanent snow cover throughout the winter in these regions. Precipitation amounts vary from region to region but are generally distributed fairly evenly throughout the year.<sup>67</sup> Due to climate change, temperatures have risen and rainfall patterns have changed in these regions. These changes highlight a situation that must be closely monitored in terms of both ecosystem management and climate-based planning.<sup>68</sup>

47.22% of Türkiye's surface area includes the characteristics of the Temperate Continental climate. This climate type is dominant in the Central Anatolia and Eastern Anatolia regions of Türkiye. The cities of Ankara, Ardahan, Bingöl, Konya, Kayseri, Sivas, Tokat and Van, located in these regions, are among the cities that can be given as examples of this climate class. Since almost half of the country exhibits temperate continental climate characteristics, not all cities with this climate were included. Ankara, Ardahan and Sivas are among the cities selected for this thesis. Due to the wide temperature range of the temperate continental climate, these cities show climatic differences within themselves.<sup>63</sup> This climate diversity, which directly affects outdoor conditions, was divided into subgroups by Köppen-Trewartha. These differences are indicated in Table 4.2.

#### **4.1.1.5. Temperate Maritime Climatic Region**

The maritime temperate climate zone is a climate type characterised by moderate temperatures and high levels of regular rainfall throughout the year. Temperature differences are limited; summers are cool, and winters are milder than in continental climates. This allows for a long growing season. Rainfall is evenly distributed throughout the year, keeping the region humid. Seasonal transitions are distinct; changes in temperature and day length throughout the year influence environmental processes. With global climate change, effects such as rising temperatures and sea level rise are being observed in these regions, highlighting the importance of infrastructure planning and climate adaptation strategies.<sup>69</sup>

Although it is a climate shaped by the effects of the sea, the Temperate Maritime Climate class is also encountered in the neighbouring cities, with the coastal cities in Türkiye. In other words, it forms a kind of buffer between the inland areas and the coastal cities. This situation can be observed more clearly in the map in Appendix C.1. 11.51% of Türkiye's surface area is covered by the Temperate Maritime climate. The cities of Balıkesir, Burdur, Edirne, Kırklareli and Uşak are shown as examples of cities that fall into this climate class.<sup>63</sup>

#### **4.1.2. Evaluation of Climatic Demands Based on Heating Degree Days and Cooling Degree Days Values**

Heating Degree Days (HDD) and Cooling Degree Days (CDD) are a basic approach used to estimate the heating and cooling energy requirements of buildings. HDD; refers to the heating energy required when the temperature falls below a certain threshold value, while CDD; refers to the cooling energy required when the temperature rises above the threshold value. Although the mentioned temperature threshold values vary in different sources, they generally vary between 15-22°C. These indicators are widely used in determining building standards and classes, calculating energy demand, creating energy policies and climate analysis.<sup>70</sup>

In this thesis study, the selection of the most suitable cities for heat transfer calculations and comparison of heating/cooling loads is important. HDD and CDD values were also examined as important parameters in these city selections. Annual data of the cities found on the website of the Turkish State Meteorological Service<sup>71</sup> were used for the HDD and CDD calculations. The Meteorological Service, which recommends a fixed calculation approach for Turkish conditions, draws attention to the importance of these calculations in terms of energy cost calculations and design parameters. In this context, HDD represents the heating load required to maintain the comfort temperature inside the building on days when the outdoor temperature falls below the determined heating threshold of 15°C (not included), while CDD represents the cooling requirement when the outdoor temperature exceeds 22°C (not included). These indicators are calculated based on daily average temperatures and play an important role in energy performance analyses, climate comparisons and building design processes on both a monthly and annual basis.

In order to make HDD and CDD values more comparable and suitable for common use, a common calculation formula was developed by the European Community Statistical Office (EUROSTAT).<sup>72</sup> According to the mentioned formulas, the calculation method for HDD and CDD values is mathematically expressed in Equation 4.1 and Equation 4.2, respectively. In these equations,  $T_m$  and  $d$  represent the daily average temperature and the number of days below the threshold value, respectively. When these

formulas are examined, HDD or CDD values are calculated as zero for cities with average daily temperatures between 15°C and 22°C.

$$\text{HDD} = (18^{\circ}\text{C} - T_m) \times d \quad \text{if } T_m < 15^{\circ}\text{C}, \text{ otherwise } 0 \quad (4.1)$$

$$\text{CDD} = (T_m - 22^{\circ}\text{C}) \times d \quad \text{if } T_m > 22^{\circ}\text{C}, \text{ otherwise } 0 \quad (4.2)$$

In the thesis study conducted, HDD and CDD calculations were calculated for all cities that could be selected. In these calculations, a total of ten years of data from 2014 to 2023 was used. These data were obtained annually by the Meteorological Service. In order to make a comparison between the cities to be selected, the average of the ten-year HDD and CDD values was taken and compared by tabulation. The annual HDD and CDD values of the six different cities selected for this study are given in Table 3.3.

Table 4.3. 10 Years (2014-2023) Averaged Yearly Formatted Heating Degree Days (HDD) and Cooling Degree Days (CDD) Values of Selected Cities

| Provinces | 10 Years Averaged, Yearly Values |      |
|-----------|----------------------------------|------|
|           | HDD                              | CDD  |
| Antalya   | 775                              | 765  |
| Şanlıurfa | 1193                             | 1206 |
| İstanbul  | 1365                             | 342  |
| Ankara    | 2248                             | 255  |
| Sivas     | 2941                             | 73   |
| Ardahan   | 4566                             | 1    |

When the data in Table 4.3 is examined, it is noticeable that the CDD values in the cities of Ardahan, Ankara and Sivas are low. These low values mean that the outdoor temperatures of the cities are already low throughout the year. In cities with low average temperatures, there is not much need for cooling in the summer months. In this context, it can be expected that the cooling loads to be calculated for these cities may be quite low.

While making HDD and CDD calculations, many important external parameters forming the boundary condition, such as relative humidity, wind speed and solar radiation, are ignored. For this reason, it should not be forgotten that HDD and CDD calculations

are made with a practical and temperature-based approach. Because calculations made with this approach only take into account sensible heating/cooling loads and ignore latent loads that become important, especially at higher/lower outdoor temperatures. In addition, the solar radiation effect is not taken into account in the calculations. These oversights, together with steady-state energy analyses, can lead to incorrect estimates of heating/cooling energy consumption.<sup>73</sup> In the thesis study, these values are simple parameters used only in city selection. In order to make the calculations more accurate, heating and cooling loads in this study are obtained with a numerical approach and time-dependent one-dimensional heat transfer calculations. In addition, solar radiation effect and relative humidity effect were also evaluated; the sky temperature value was analysed in relation to temperature, relative humidity and time-dependently.

#### **4.1.3. Evaluation of Selected Cities Based on Solar Radiation Maps**

Heat transfer analyses are a very important tool for accurately predicting the responses of a building to environmental conditions. In these analyses, not only the temperature difference but also solar radiation is a critical parameter to be considered, as it directly affects heat gains. Especially since horizontal or inclined surfaces, such as roofs, are exposed to direct solar radiation throughout the day, the radiative heat gains that occur here seriously affect the indoor comfort and energy consumption of the building. Therefore, in the selection of cities where heat transfer calculations will be made, not only the climate classification but also the regional solar potential on a city basis should be analysed.

Solar radiation is the energy emitted by electromagnetic waves and is one of the main sources of passive heat gains in buildings. Solar radiation is an indispensable input for radiative heat transfer calculations. In transient heat transfer analyses, radiative gains vary according to the time of day, season of the year, surface orientation and atmospheric conditions. Therefore, in time-dependent analyses, solar radiation should not be modelled with a fixed value, but according to radiation data that varies with time. Thus, the total energy input to which the building is exposed during the day can be calculated more realistically.<sup>74</sup>

Solar radiation calculations take into account three main components: direct radiation, diffuse radiation and reflected radiation. While direct radiation is dominant, especially on roof surfaces, diffuse components also gain importance in dense urban textures.<sup>75</sup> This radiation data can be obtained from different data sources. Although databases such as PVGIS, NASA or Meteonorm are widely used worldwide, the seasonal solar radiation map published by the Meteorological Service, which provides more local and reliable data specific to Türkiye, was used as the basis for the city selection phase in this study.<sup>76</sup> These maps include the average solar radiation distribution of 18 years of data from 2004 to 2021. Solar gain maps provide daily average annual data for all cities, seasonally in kWh/m<sup>2</sup>day units. When the maps showing the average values of solar gains are examined in Figure 4.3, it is seen that there is a decreasing gradient in the solar radiation distribution from the south to the north of Türkiye. For this reason, the latitudes of the cities are a determining factor for solar radiation gain. The latitudes of the selected cities were tried to be distributed proportionally within Türkiye, which is located in a narrow latitude belt. Six cities located in different climatic zones of Türkiye were determined through the relevant maps, and the solar potential in summer and winter (Appendix C.2, Appendix C.3) seasons were compared manually for each.

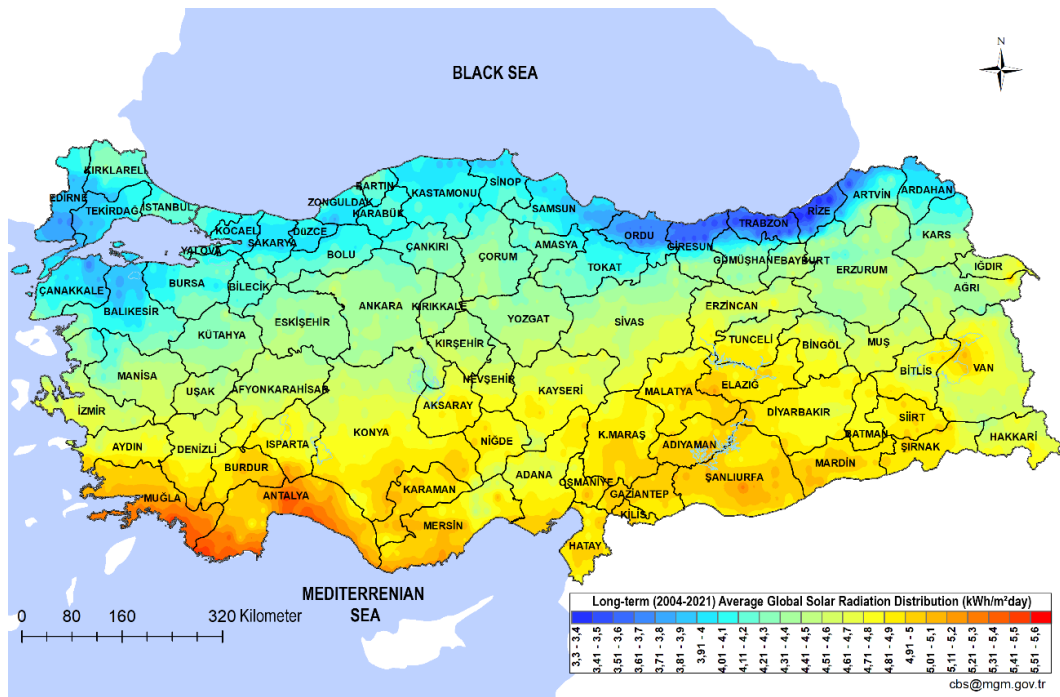


Figure 4.3. Map of Average Global Solar Radiation Distribution of Türkiye (Source: Turkish State Meteorological Services)

The selected cities were distributed evenly from regions with low, medium and high radiation. Thus, it was possible to examine how both heating and cooling loads change under different radiation conditions. In this context, solar radiation is not only a visual reference but also a data source that provides direct input to computational models. This data was evaluated visually in the selection of cities. With these selections, it was aimed to compare time-dependent heat transfer calculations and obtain meaningful results.

In conclusion, solar radiation maps are powerful tools that allow the city selection process to be based on scientific foundations. In order to obtain more realistic results in time-dependent heat transfer calculations, regional radiation data should be taken into account.<sup>77</sup> In this way, the energy behaviour of building components that are in constant interaction with the external environment, such as roofs, can be accurately modelled. Solar radiation maps are an indispensable reference point for analyzing building energy performance, guiding material selection, and making design decisions based on climatic strategies.

#### **4.1.4. Justification of Case Study City Selections Through Thermal Discomfort Analysis**

The psychrometric diagram stands out as a highly functional tool that is suitable for comparisons between different zones in the design and analysis processes aimed at ensuring human comfort in interior spaces. This diagram graphically presents the thermodynamic behavior of humid air and thus allows the temperature, humidity and other physical properties of the ambient air to be evaluated together. The main environmental variables affecting human comfort include dry bulb temperature, relative humidity, absolute humidity, wet bulb temperature, dew point temperature and saturation curve. The psychrometric diagram combines these variables on a single graph, making it easier to understand the current state of the air and determine the necessary interventions.<sup>78</sup>

In addition to traditional parameters, modern psychrometric analyses have begun to take into account factors that directly affect human comfort, such as average radiant

temperature, air movement and metabolic rate. The integration of these additional variables enables more flexible and adaptive design approaches, going beyond comfort zones defined by fixed boundaries. Thus, the diagram reflects the interaction between the physical environment and humans in a more realistic way, allowing for the development of a user-oriented and dynamic understanding of comfort. People's perception of thermal comfort is affected not only by temperature and humidity, but also by environmental factors such as illumination level, sound level and individual physiological characteristics. For example, skin temperature changes in direct relation to ambient temperature and plays a decisive role in individuals' comfort assessments. For this reason, psychrometric diagrams are a powerful visual analysis tool that not only presents physical environment data but also provides meaning to physiological responses.<sup>79</sup>

In this thesis, psychrometric analysis was performed for six different cities. As a result of this analysis, it was determined how far the outdoor conditions of the cities were from the thermal comfort limits. In order to create a psychrometric chart, long-term outdoor data of a city is needed. The necessary outdoor data was obtained from the open-access website of the climate.onebuilding organization.<sup>80</sup> The data obtained from this website is in EnergyPlus Weather Data format. The files in this format contain many climate data such as outdoor temperature, relative humidity, atmospheric pressure, direct and diffuse solar radiation and wind speed in hourly time resolution. These data are of fundamental importance for the simulation of heating, cooling, lighting, ventilation, and general energy flows in buildings.<sup>81</sup> In order to create a psychrometric chart, the epw file containing the average of the data from 2009 to 2023 was used.

In order to create a Psychrometric chart with the obtained data, the Climate Consultant program version 6.0 was used. Thermal comfort zone calculations in this thesis are based on ASHRAE Standard 55 and the Current Handbook of Fundamentals Model defined in the program.<sup>82,83</sup> Climate Consultant combines these standards to optimize building design for energy efficiency and user comfort. However, the information about which editions of these standards are used is not communicated to the user. For this reason, the most up-to-date version of these standards is presented as a reference. Accordingly, general evaluations for the 6 selected cities are given below with the relevant schematic representation:

- Ankara, in January, due to low temperature and humidity, comfort is extended outside, serious heating starts. Although the temperature increases in the July season, full comfort cannot be provided due to low humidity. (Appendix D.1, Appendix D.2)
- While Antalya experiences conditions relatively close to the comfort zone in January, high temperatures and humidity in July cause deviations from comfort and require intensive cooling. (Appendix D.3, Appendix D.4)
- Ardahan is far from the comfort zone in the winter months due to very low temperature and humidity; in the summer months, the values approach comfort to a limited extent. The heating load is dominant throughout the year. (Appendix D.5, Appendix D.6)
- Although the values in Istanbul in January are close to the comfort zone, they are not fully sufficient due to the low temperature. In July, the comfort zone is exceeded due to the increase in temperature and humidity. Accordingly, the monthly average minimum and maximum values in the psychrometric graph for January and July are shown in Figure 4.4 and Figure 4.5 together with the thermal comfort zone.

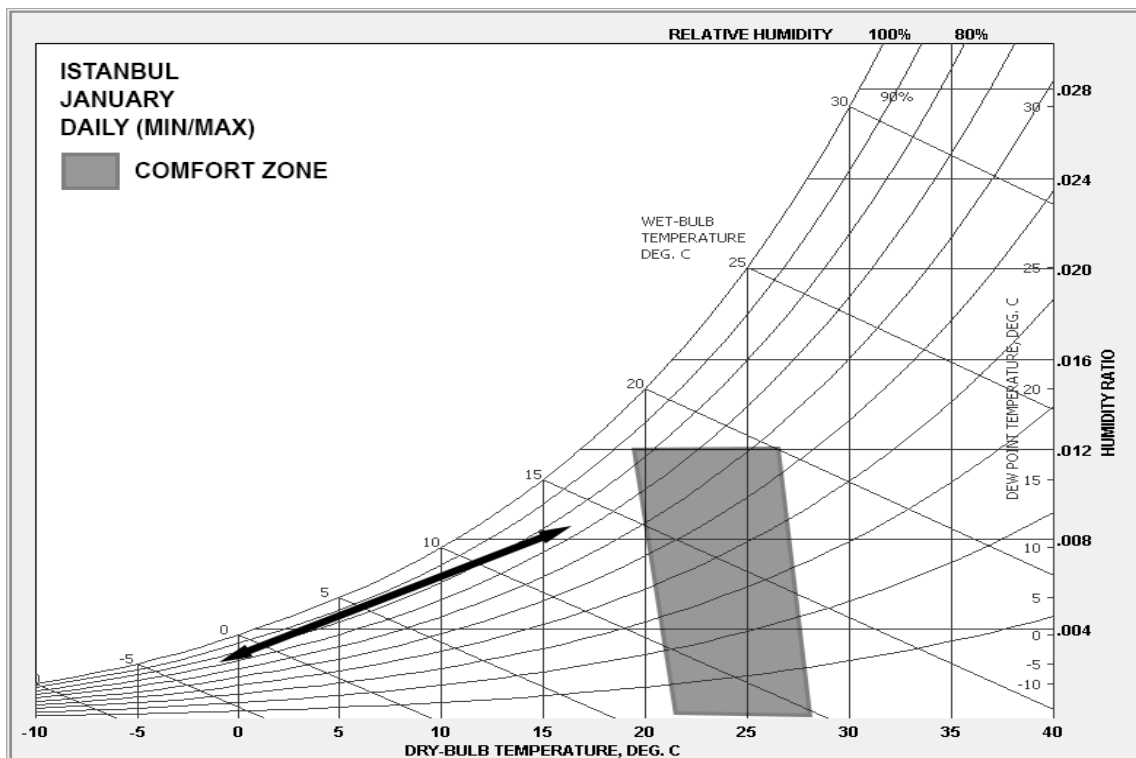


Figure 4.4. Psychrometric Chart of Comfort Zones January in İstanbul

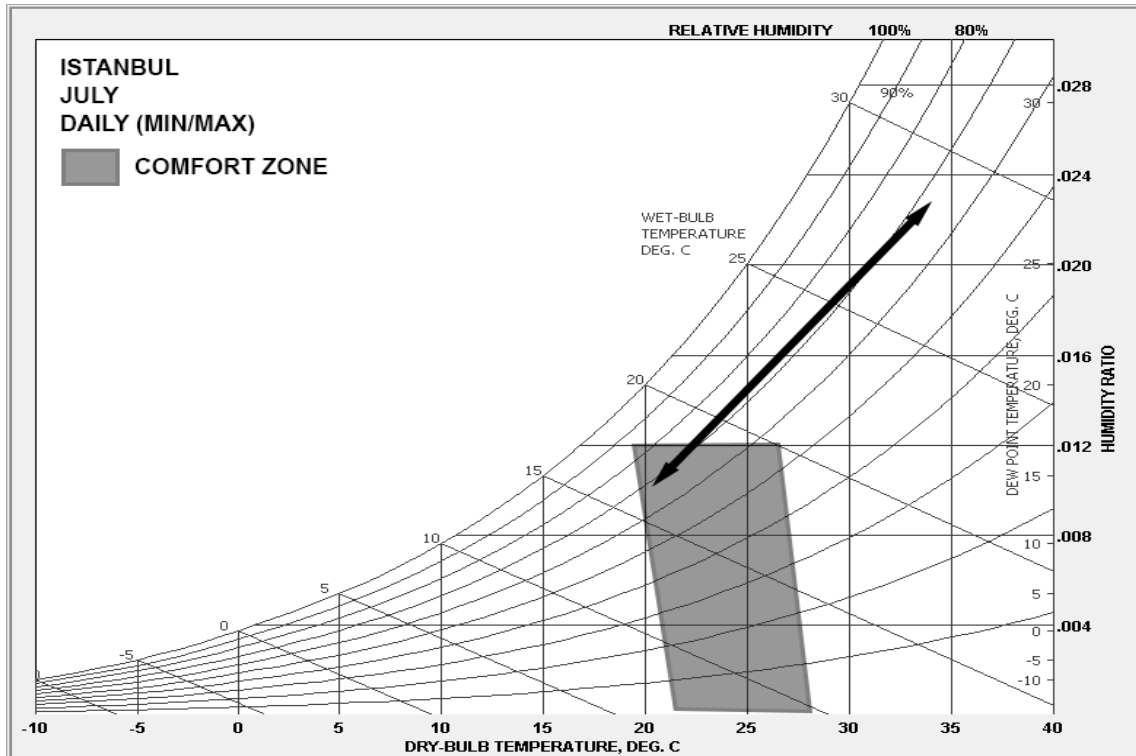


Figure 4.5. Psychrometric Chart of Comfort Zones July in İstanbul

- Sivas is well outside the comfort zone in January due to low temperature and humidity, which creates a significant heating need. In July, despite the increase in temperature, full comfort cannot be achieved due to low humidity; this situation sometimes creates a cooling need. (Appendix D.7, Appendix D.8)
- Şanlıurfa, due to the combination of low humidity in January and extreme heat and low humidity in July, comfort conditions are almost never achieved. (Appendix D.9, Appendix D.10)

These psychrometric analyses show that indoor comfort conditions cannot be achieved without air conditioning systems during hot and cold periods of the year in six different cities. This situation indicates significant energy requirements for both heating and cooling, and reveals that city-based differences should be taken into account in time-dependent heat transfer analyses.

In this context, analysis results were obtained with daily minimum/maximum values for six different cities. Monthly average minimum/maximum values for January and July are marked with arrowhead lines. The thermal comfort zone is highlighted with

a colored area. The analyses for Istanbul for January and February are given in Figure 4.4 and Figure 4.5, respectively. Psychrometric charts for other cities are given in Appendix D.1, Appendix D.2 etc.

## **4.2. Roof Construction and Thermal Performance Parameters**

Within the scope of the thesis, two different roof typologies were selected in order to represent the construction practices and climatic responses observed in different climatic regions of Türkiye. These are: flat terrace roof and tile-covered concrete structure roof systems. Each roof type exhibits different thermal behaviours, construction methods and layer arrangements, and plays a determining role in the heat transfer through the building envelope. The selection of these roof types was made both because they are widely used in the building stock in Türkiye and because they represent the practices encountered in different climatic regions. While the flat roof type is generally preferred in hot climate regions and urban, compact building designs, the gable roof type is widely used in cold and transitional climates due to its advantage of easy rain and snow load drainage. The terrace roof is a system preferred mostly in temperate climates to provide additional open space function. The comparative analysis of these different roof types allows the evaluation of the effect of the roof structure on thermal performance and prepares the ground for a detailed examination of the contribution of insulation strategies and material properties to energy efficiency under different climatic conditions.

Roofs are one of the important elements in terms of energy performance in buildings. The energy efficiency of this element varies depending on many parameters such as the external conditions of the region where the structure is located, the form of the roof, the slope, the materials used and the total number of floors in the structure.<sup>84</sup> For this reason, when we look at the historical development of roofs, we see that they are generally shaped in accordance with the climate conditions they are in. For example, igloos used in polar climates, with their thick wall mass and dome-shaped roof that directs the wind, can maintain their interior temperatures above the freezing point while the exterior temperatures are around -30°C.<sup>85</sup> Similarly, the roofs of the Harran houses located in the Southeastern Anatolia Region of Türkiye, where hot and dry climate conditions are seen, are designed in harmony with the climate. These roofs, Thanks to

their steeply sloped conical dome forms, provide passive ventilation by allowing the heated air in the interior to exit through the opening at the top of the conical structure. Their thick walls, with their high thermal capacity, store energy in the summer period when there are high temperatures and intense solar radiation, while with their dry climate, they provide energy efficiency by allowing the structural elements to cool down with the decreasing temperature at night and the sky radiation effect.<sup>86</sup>

Roof systems contribute to sustainability not only with thermal insulation but also with functional design features such as efficient rainwater collection, natural ventilation, and sunlight redirection.<sup>87</sup> Such multifunctional solutions play an important role in the inclusion of buildings in the Nearly Zero Energy Buildings (NZEB) class.

For all these reasons, research on the architectural form, material properties and climate interaction of roof systems is important in terms of energy efficiency and sustainable building design. Detailed evaluations on the thermal performance of roofs contribute to the development of strategies that will directly affect the overall energy performance of the building. In this context, in the next heading, the layered structure details of the roof typologies used in the study and the thermal properties of these systems will be discussed in detail.

#### **4.2.1. Roof Typologies and Thermal Layer Compositions**

In this thesis, two different roof typologies were selected for one-dimensional time-dependent heat transfer calculations. These roof types were selected because they are widely used in all climatic regions of Türkiye. In this way, energy performance analyses of roof types commonly used in both rural and urban areas are performed in this thesis study, contributing to a more accurate selection of roofs in terms of energy performance in newly constructed structures. Within the scope of this subheading of the thesis, the thermal properties of the materials of the two different roof types in question, material alignments along the roof cross-section and the properties of the insulation material deemed appropriate for both roofs will be discussed. Overall Heat Transfer Coefficient values were calculated for each roof and insulation thicknesses that are in accordance with the TS825 standard were defined for these values.

While calculating the insulation thickness, four different situations were created in terms of U-value and these situations were compared in terms of energy performance. Basically, one-dimensional time-dependent heat transfer calculations were made for uninsulated roofs. Then, as given in Table 4.4, one-dimensional time-dependent heat transfer calculations were made again by providing the U-values required in both the old and current TS825 standards. In addition to these, one-dimensional time-dependent heat transfer calculations were made by providing the U-values specified in the UK Building Regulation<sup>16</sup> (Appendix E.1), which demands better U-value values. According to the recommendations of this regulation, the maximum U-value value expected to be met in roofs is 0.16 W/m<sup>2</sup>K, while the maximum U-value values provided by the insulated roof groups classified as High Insulated in the thesis study are 0.15 W/m<sup>2</sup>K. Accordingly, four different situations emerge that can be compared specifically for a single roof type. This situation adds value to this thesis in terms of examining the effect of insulation thickness on heat transfer rate in different typologies and sloped roofs.

Table 4.4. Recommended U-Values for Roofs both in older TS825 and Current TS825 Standart

| Old TS825 Standart |           |                                         | Revised TS825 Standart |           |                                         |
|--------------------|-----------|-----------------------------------------|------------------------|-----------|-----------------------------------------|
| Regions            | Provinces | U-Value Thresholds (W/m <sup>2</sup> K) | Regions                | Provinces | U-Value Thresholds (W/m <sup>2</sup> K) |
| 1                  | Antalya   | 0.45                                    | 1                      | Antalya   | 0.35                                    |
| 2                  | İstanbul  | 0.40                                    | 2                      | Şanlıurfa | 0.3                                     |
|                    | Şanlıurfa |                                         | 3                      | İstanbul  | 0.3                                     |
| 3                  | Ankara    | 0.30                                    | 4                      | Ankara    | 0.25                                    |
| 4                  | Ardahan   | 0.25                                    | 5                      | Sivas     | 0.2                                     |
|                    | Sivas     |                                         | 6                      | Ardahan   | 0.2                                     |

#### 4.2.1.1. Use of Extruded Polystyrene (XPS) as Roof Insulation Material

One of the most effective ways to increase energy efficiency in buildings is through insulation applications in the building envelope. Interiorinsulation, especially integrated into roof and wall sections, contributes greatly to providing thermal comfort in interior spaces by reducing energy demand. Insulation applications, which are considered an indispensable technology for sustainable building designs today and in the future, both provide energy savings and increase structural performance.<sup>88</sup>

Materials commonly used for insulation purposes on roofs include Mineral Wool, Rock Wool, Polyethylene, Expanded Polystyrene (EPS), Fiberglass, Cellulose and Extruded Polystyrene (XPS). In this study, XPS material was preferred among the options in question. The reason for choosing XPS, which offers multiple advantages, is the versatility it offers and its ability to provide long-term performance in roof systems. XPS has a structure that is highly resistant to moisture absorption thanks to its closed-cell structure. With this feature, it can continue its function without being affected by condensation that may occur in the inner layers, especially in sandwich structure systems. At the same time, thanks to its plastic-based structure, problems such as rotting, mold or biological decomposition are not observed even after long-term use. The material's resistance to pressure is also quite high; it can structurally withstand loads between 103 and 689 kilopascal pressure while maintaining its form. In addition, XPS is a sustainable option both economically and environmentally, thanks to its reusability. Even when it has reached the end of its useful life, it can be cleaned, processed and re-evaluated in different areas, such as in the production of outdoor elements or insulation products.<sup>89</sup>

XPS also exhibits a very successful profile in terms of thermal properties. As shown in Table 4.5; while it offers high insulation capacity thanks to its low thermal conductivity coefficient ( $k = 0,034 \text{ W/m}\cdot\text{°C}$ ), when evaluated with its low density ( $35 \text{ kg/m}^3$ ) and specific heat ( $1400 \text{ J/kg}\cdot\text{°C}$ ), the thermal diffusivity value of the material ( $k/\rho C_p = 6,93 \cdot 10^{-7} \text{ m}^2/\text{s}$ ) remains at very low levels. This means that XPS conducts heat late and helps maintain the indoor temperature balance. As a result, XPS material offers a high-performance and long-lasting insulation solution for roof systems in both physical and thermal terms. In this context, XPS was preferred as the thermal insulation material within the scope of the thesis.

#### **4.2.1.2. Flat Terrace Roof and Properties**

Flat roofs used in buildings can vary greatly in terms of their intended use. While some flat roofs create an additional shell by using shading elements, some terrace roofs provide ground for green roofs. Apart from these, flat terrace roofs, which are also very suitable for photovoltaic panel installation, are roof types encountered all over the world. The flat roof used in one-dimensional time-dependent heat transfer calculations in this

thesis was created as an open-top walkable terrace roof in order to better examine the effects of solar radiation. Flat roofs have many advantages such as wide usage area, transformable structure and being suitable for integrated systems. The most important disadvantages of these roofs are humidity and moisture transfer due to rainwater accumulation.<sup>90</sup> For this reason, water and moisture insulation are as important as thermal insulation on flat roofs. Moisture transfer calculations are not included in this thesis.

In this thesis study, attention was paid to realistic material selection and heat transfer calculations for all roof cases. Thus, it was aimed to examine the thermal effect of even the smallest material layer in time-dependent heat transfers. Ceramic was preferred as the outer surface material in this roof type designed as a walkable terrace roof. Thermal properties of all materials used for time-dependent heat transfer calculations in the thesis process were obtained through the DesignBuilder program version 7.02.006<sup>40</sup> using the Energyplus 9.4 database. For two roof cases, absorptivity ( $\alpha$ ) and emissivity ( $\epsilon$ ) values were obtained from the Energyplus material library as 0.6 and 0.9, respectively. These two values remain constant for all roof types. In addition, in the flat terrace roof type, where waterproofing is needed the most, the waterproof membrane layer was used in two layers compared to the sloping cases.

According to the material composition schematized in Figure 4.6, the thicknesses of the materials are; 1.2 cm for ceramic tile, 0.8 cm for adhesive mortar, 0.6 cm for double-layer waterproof membrane, 5 cm for leveling screed, 15 cm for reinforced concrete slab, 1 cm for interior base plaster and 0.5 cm for interior finishing plaster, respectively. The thickness of XPS, which is a thermal insulation material, varies from city to city and according to U-values.

In this context, the thermal insulation thicknesses required for each case and city are given in Table 4.6. Based on this table, for flat terrace roof, for old TS825, an insulation thickness of 6 cm to 12 cm was assigned, which will vary from city to city, and for new TS825, this range varies between 9 cm and 16 cm. High Insulation calculation was kept constant with an insulation application of 22 cm for all cities and roofs. The U-values corresponding to these insulation thicknesses are small values such as 0.14 and 0.15 W/m<sup>2</sup>K for terrace roofs and inclined reinforced concrete carrier roofs, respectively.

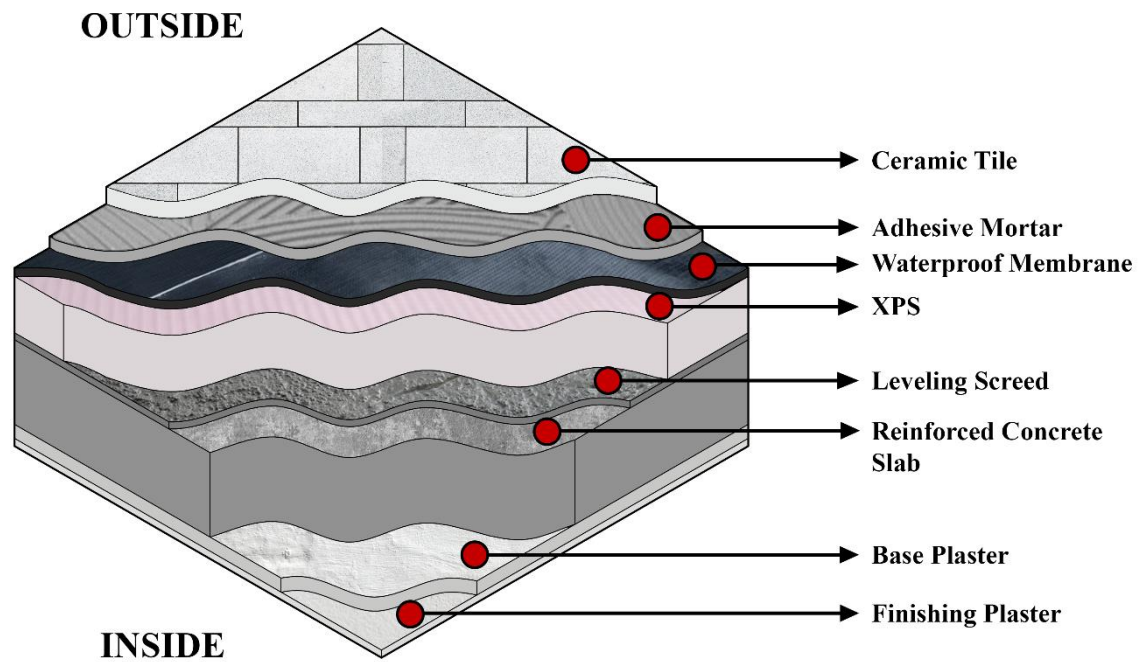


Figure 4.6. The Material Composition of Flat Terrace Roofs

#### 4.2.1.3. Sloped Roof with Concrete Structure and Properties

Reinforced concrete carrier sloped roof systems are one of the roof types that offer advantages in terms of both structural durability and energy efficiency, which are widely used in regions with different climatic conditions today. These roofs, usually made of reinforced cement concrete (RCC), can exhibit different thermal behaviours depending on the type of coating applied to the roof surface. Thanks to the natural drainage opportunity provided by the slope and its contribution to the general stability of the structure, it is especially preferred in regions with heavy rainfall and snowfall.

Table 4.5. Material Compositions and Thermal Properties of All Roof Cases

| Roof Type                           | Material Name              | Material Thickness (cm) | Total Thickness (cm)           | Thermal Conductivity (k)<br>(W/m°C) | Density (ρ)<br>(kg/m³) | Specific Heat (Cp)<br>(J/kg°C) | Diffusivity<br>(k/ρ * Cp) |
|-------------------------------------|----------------------------|-------------------------|--------------------------------|-------------------------------------|------------------------|--------------------------------|---------------------------|
| Flat Terrace Roof                   | Ceramic Tile               | 1.2                     | 24.1 cm + Insulation Thickness | 1.4                                 | 2500                   | 840                            | $6.67 \times 10^{-7}$     |
|                                     | Adhesive Mortar            | 0.8                     |                                | 0.38                                | 1120                   | 840                            | $4.04 \times 10^{-7}$     |
|                                     | Waterproof Membrane (2x)   | 0.6                     |                                | 0.23                                | 1100                   | 1000                           | $2.09 \times 10^{-7}$     |
|                                     | Thermal Insulation (XPS)   | Varies                  |                                | 0.034                               | 35                     | 1400                           | $6.94 \times 10^{-7}$     |
|                                     | Leveling Screed            | 5                       |                                | 0.41                                | 1200                   | 840                            | $4.07 \times 10^{-7}$     |
|                                     | Reinforced Concrete Slab   | 15                      |                                | 2.5                                 | 2400                   | 1000                           | $1.04 \times 10^{-6}$     |
|                                     | Interior Base Plaster      | 1                       |                                | 0.42                                | 1200                   | 840                            | $4.17 \times 10^{-7}$     |
|                                     | Interior Finishing Plaster | 0.5                     |                                | 0.51                                | 1120                   | 960                            | $4.74 \times 10^{-7}$     |
|                                     |                            |                         |                                |                                     |                        |                                |                           |
| Sloped Roof with Concrete Structure | Roof Tile                  | 1.2                     | 14.6 cm + Insulation Thickness | 0.84                                | 1900                   | 800                            | $5.53 \times 10^{-7}$     |
|                                     | Timber Nail Board          | 1.6                     |                                | 0.12                                | 540                    | 1210                           | $1.84 \times 10^{-7}$     |
|                                     | Waterproof Membrane        | 0.3                     |                                | 0.23                                | 1100                   | 1000                           | $2.09 \times 10^{-7}$     |
|                                     | Thermal Insulation (XPS)   | Varies                  |                                | 0.034                               | 35                     | 1400                           | $6.94 \times 10^{-7}$     |
|                                     | Reinforced Concrete Slab   | 10                      |                                | 2.5                                 | 2400                   | 1000                           | $1.04 \times 10^{-6}$     |
|                                     | Interior Base Plaster      | 1                       |                                | 0.42                                | 1200                   | 840                            | $4.17 \times 10^{-7}$     |
|                                     | Interior Finishing Plaster | 0.5                     |                                | 0.51                                | 1120                   | 960                            | $4.74 \times 10^{-7}$     |
|                                     |                            |                         |                                |                                     |                        |                                |                           |
|                                     |                            |                         |                                |                                     |                        |                                |                           |

Table 4.6. Insulation Thicknesses with Provided U-values for All Roof and Insulation Cases

| Roof Type                           | Provinces | Uninsulated                           |                           | Insulation Dependence                 |                           |                                       |                           |                                       |                           |
|-------------------------------------|-----------|---------------------------------------|---------------------------|---------------------------------------|---------------------------|---------------------------------------|---------------------------|---------------------------------------|---------------------------|
|                                     |           |                                       |                           | Old TS825                             |                           | Current TS825                         |                           | High Insulation                       |                           |
|                                     |           | Provided U-value (W/m <sup>2</sup> K) | Insulation Thickness (cm) | Provided U-value (W/m <sup>2</sup> K) | Insulation Thickness (cm) | Provided U-value (W/m <sup>2</sup> K) | Insulation Thickness (cm) | Provided U-value (W/m <sup>2</sup> K) | Insulation Thickness (cm) |
| Flat Terrace Roof                   | Antalya   | 2.27                                  | x                         | 0.45                                  | 6                         | 0.32                                  | 9                         | 0.14                                  | 22                        |
|                                     | Şanlıurfa | 2.27                                  | x                         | 0.4                                   | 7                         | 0.3                                   | 10                        | 0.14                                  | 22                        |
|                                     | İstanbul  | 2.27                                  | x                         | 0.4                                   | 7                         | 0.3                                   | 10                        | 0.14                                  | 22                        |
|                                     | Ankara    | 2.27                                  | x                         | 0.3                                   | 10                        | 0.25                                  | 12                        | 0.14                                  | 22                        |
|                                     | Sivas     | 2.27                                  | x                         | 0.25                                  | 12                        | 0.19                                  | 16                        | 0.14                                  | 22                        |
|                                     | Ardahan   | 2.27                                  | x                         | 0.25                                  | 12                        | 0.19                                  | 16                        | 0.14                                  | 22                        |
| Sloped Roof with Concrete Structure | Antalya   | 2.47                                  | x                         | 0.41                                  | 7                         | 0.33                                  | 9                         | 0.15                                  | 22                        |
|                                     | Şanlıurfa | 2.47                                  | x                         | 0.36                                  | 8                         | 0.3                                   | 10                        | 0.15                                  | 22                        |
|                                     | İstanbul  | 2.47                                  | x                         | 0.36                                  | 8                         | 0.3                                   | 10                        | 0.15                                  | 22                        |
|                                     | Ankara    | 2.47                                  | x                         | 0.3                                   | 10                        | 0.25                                  | 12                        | 0.15                                  | 22                        |
|                                     | Sivas     | 2.47                                  | x                         | 0.25                                  | 12                        | 0.2                                   | 16                        | 0.15                                  | 22                        |
|                                     | Ardahan   | 2.47                                  | x                         | 0.25                                  | 12                        | 0.2                                   | 16                        | 0.15                                  | 22                        |

Due to its high thermal mass, concrete contributes to indoor comfort, but it can also cause excessive heating, especially in summer, by transferring the energy it absorbs from the sun to the interior.<sup>91</sup> Therefore, it is important to minimize undesirable situations with appropriate insulation applications. On the other hand, when the detailed solutions in reinforced concrete walls and roofs are insufficient, thermal bridge formation can be observed; this situation can decrease energy efficiency and increase heat loss from the structure.<sup>92</sup> In order to prevent this situation, wood material with a low heat conduction coefficient and spreading speed was preferred in the material arrangement that can create a thermal bridge in this case of the thesis.

When looking at the Istanbul Zoning Regulation,<sup>93</sup> although there is no lower limit for the angle of inclination for sloping roofs, there is a 45% upper limit for the angle of inclination. On roofs with a slope below 20%, possible snow load accumulation and negative effects on liquid flows can be observed. For example, as a result of the growth of various weeds on tile roofs where liquid accumulation occurs, deformations occur on the roof surface and, accordingly, negative results are experienced in the performance and life of the roof.<sup>94</sup> In this context, the angle of inclination, which is the average of 20% and 45%, 30°, was preferred in this thesis study.

In applications made in hot and humid climates, even if such roofs are supported with different surface coatings, ceiling and interior air temperatures may not be sufficient to provide user comfort from time to time. This situation occurs as a result of the high heat retention capacity of concrete and the transfer of heat accumulated during the day to the interior until night hours.<sup>95</sup> In this context, not only insulation but also the integration of natural ventilation systems into the roof design is gaining importance.<sup>96</sup> As a result, although reinforced concrete sloping roofs can provide advantageous systems in terms of energy, climatic conditions, material selection, construction details, and the integration of passive strategies are the main factors that determine the success of this performance. Designing these systems to be used in different climates with the support of detailed analyses is of critical importance in terms of maximizing both user comfort and energy efficiency. In this thesis, time-dependent one-dimensional heat transfer calculations for the sloping reinforced concrete roof were made, and its thermal performances at different U-values were analysed.

The thermal properties of the reinforced concrete carrier roof materials used in the thesis are given in Table 4.5. Also, when Figure 4.7 is examined, the composition of these materials is given schematically. The thicknesses of the materials shown in the given figure are; 1.2 cm for roof tile, 1.6 cm for timber nail board, 0.3 cm for membrane, 10 cm for reinforced concrete slab, 1 cm for interior base plaster and 0.5 cm for interior finishing plaster. Here, the thickness of the thermal insulation material XPS varies from city to city. In this context, the thermal insulation thicknesses required for each case and city are given in Table 4.6. Based on this table, the insulation thickness for the sloped roof with concrete structure is assigned between 7 cm and 12 cm, which will vary from city to city, for the old TS825, and for the new TS825, this range varies between 9 cm and 16 cm.

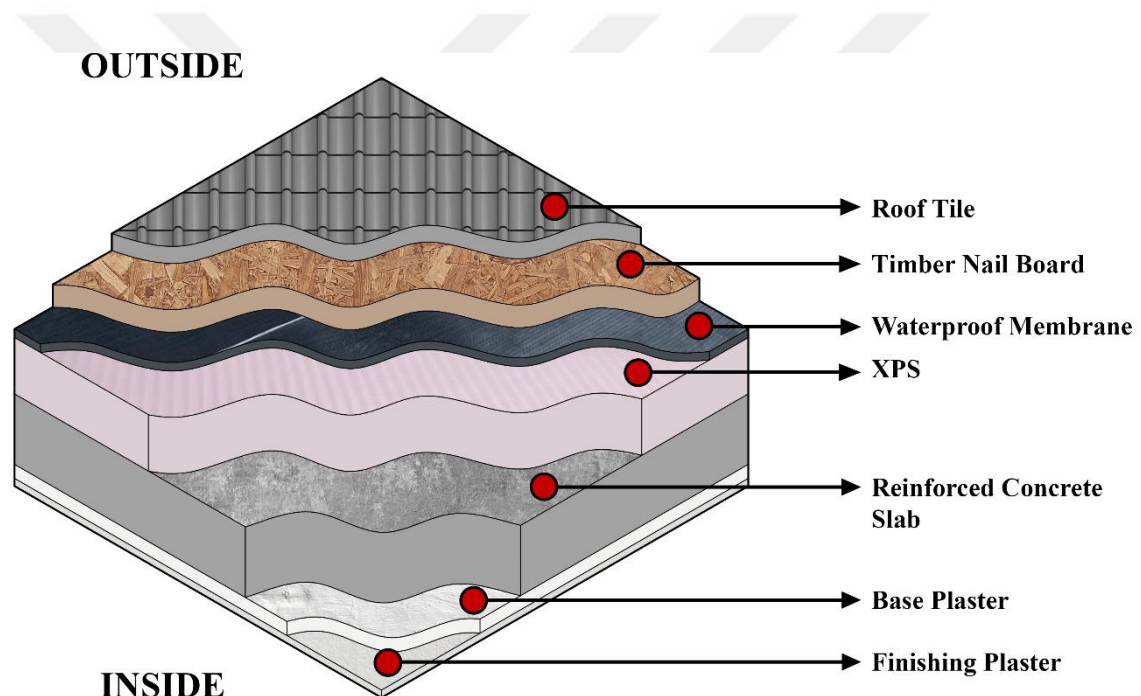


Figure 4.7. The Material Composition of Sloped Roof with Concrete Structure

In this type of roof, the reinforced concrete carrier layer is kept smaller than in flat terrace roofs due to the slope. Because in this type of roofs, the main task of the carrier is not to serve the life on it but to ensure the integrity of the roof.

## **CHAPTER 5**

### **RESULTS AND DISCUSSIONS**

In this chapter, the thermal performance of the building envelope under different insulation scenarios is evaluated based on the numerical analyses performed. Within the scope of the study, temperature distribution results obtained in January and July for the provinces of Antalya and Ardahan, which represent different climate zones, are presented. Temperature changes occurring throughout the material thickness and at different times of the day were obtained through time-dependent analyses, and the way in which the heat transfer mechanism varies depending on the insulation level and climatic conditions was analysed in detail. Based on these analyses, heat transfer rates, interior surface temperature differences, and the effects of insulation on energy efficiency were quantitatively presented in the following sections.

Accurately determining the amount of heat passing through the building envelope is critical to understanding thermal insulation performance. Therefore, obtaining time-dependent temperature distributions forms the basis of heat transfer analyses. Heat flow calculations are based on Fourier's law of heat conduction and require accurate knowledge of temperature gradients. Especially in multi-layered structural elements, the temperature differences between the inner and outer surfaces at each time step exhibit significant variability under transient conditions. Therefore, analysing the temperature distribution in wall and roof sections under different insulation scenarios and climatic conditions is of utmost importance for both ensuring thermal comfort and minimising energy losses. In this context, temperature distribution graphs were obtained for two roof types and four different insulation scenarios for the cities of Antalya and Ardahan, which form the two extreme boundaries in the current TS825 standard, for the months of January and July. These temperature distributions are presented in Figures 5.1, 5.2, 5.3, and 5.4, respectively.

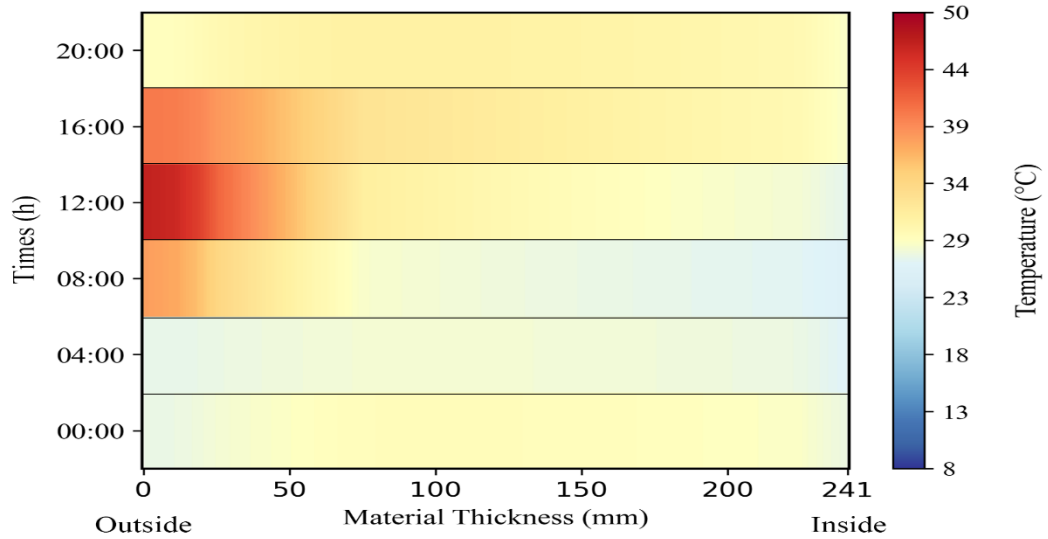


Figure 5.1. Temperature Distribution Through a Flat Roof in Antalya with Uninsulated Scenario in July

Figure 5.1 shows the temperature distribution for an uninsulated flat roof in Antalya in July. According to this, the outdoor surface temperature varies between 34 °C and 46 °C at midday. The fact that the indoor surface temperature is 1-2 °C higher than at other times of the day during these hours indicates that heat transfer is intense at these times. However, throughout the day, the indoor temperature is 3-5 °C higher than the fixed indoor temperature of 24 °C set for July. This situation creates high heat transfer for the uninsulated flat terrace roof scenario in July.

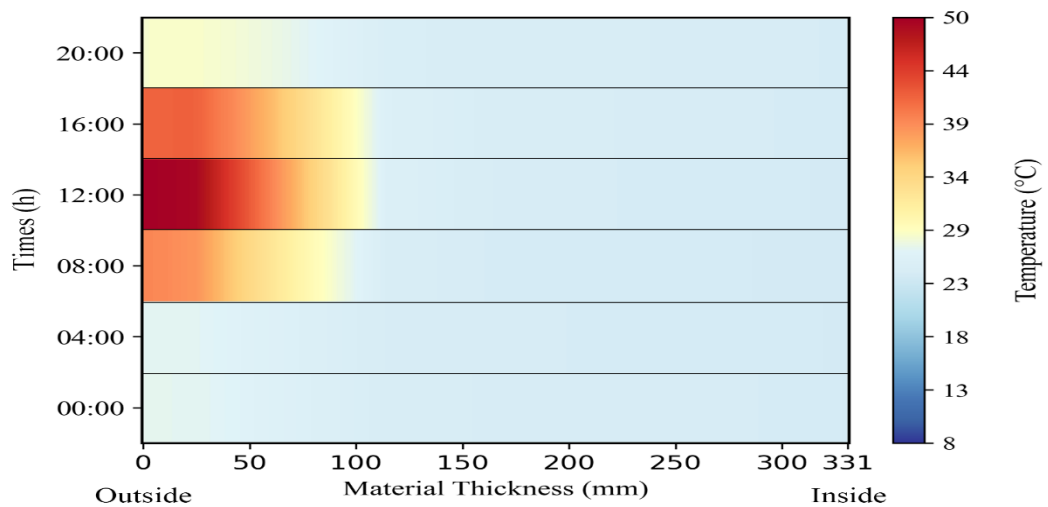


Figure 5.2. Temperature Distribution Through a Flat Roof in Antalya with Current TS825 Insulation Scenario in July

Figure 5.2 shows the temperature distribution data for July for the insulated with the current TS825 flat roof in Antalya. According to this graph, the external surface temperature varies between 40 °C and 45 °C at midday. The insulation, which starts at 26 mm and ends at 116 mm thickness, is seen to perform well even during peak load hours. In this context, the difference between the surface temperature and the indoor temperature reaches a maximum of 0.6 °C during the day.

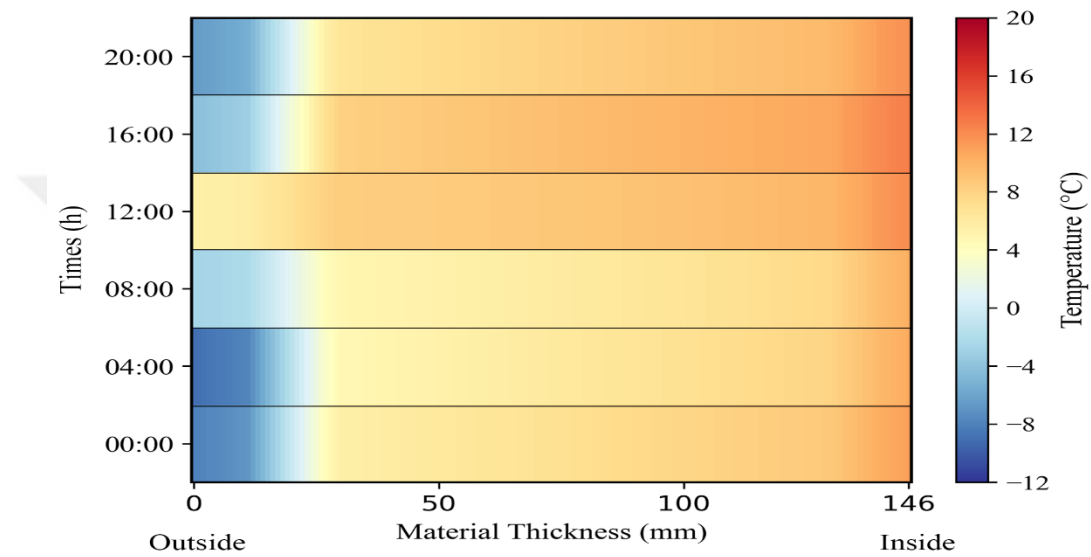


Figure 5.3. Temperature Distribution Through a Concrete Structured Roof in Ardahan with Uninsulated Scenario in January (South Oriented with 30° Angle)

Figure 5.3 shows the temperature distribution for an uninsulated concrete structure roof in Ardahan city for January. According to this graph, it can be seen that the surface temperatures inside the building are 8 to 10 °C lower than the ambient temperatures throughout the day. Such low interior surface temperatures negatively impact thermal comfort, result in a significant increase in heating load, and create an environment conducive to potential condensation risks. Therefore, the use of an uninsulated roof system in such cases does not provide a suitable solution in terms of energy efficiency and interior thermal comfort.

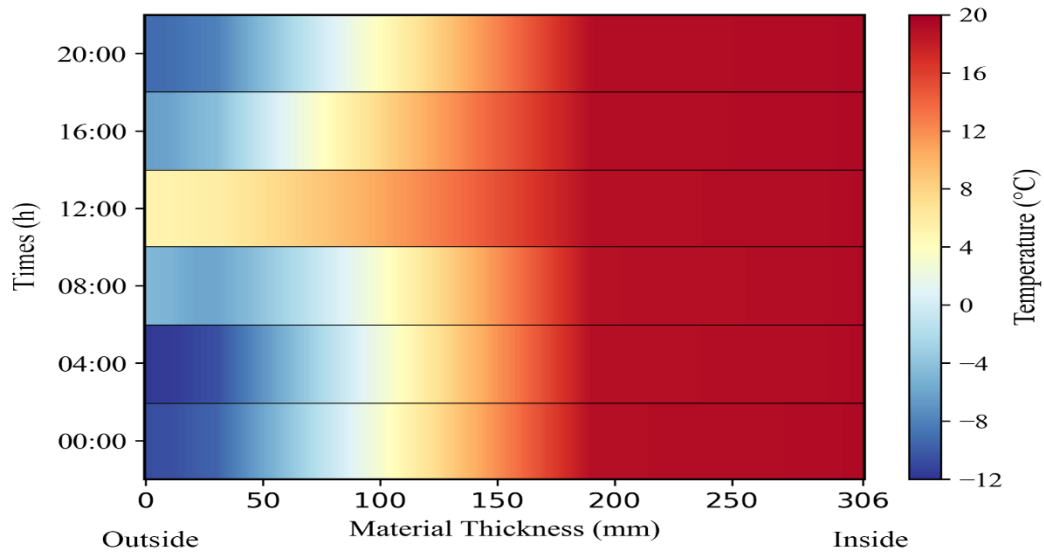


Figure 5.4. Temperature Distribution Through a Concrete Structured Roof in Ardahan with Current TS825 Insulation Scenario in January (South Oriented with 30° Angle)

Figure 5.4 shows the temperature distribution for January for the insulated with current TS825 concrete structured roof belonging to the city of Ardahan. As seen in the graph, the temperature values in areas close to the inner surface are significantly higher than the external ambient temperatures, and the average inner surface temperature closely matches the heated indoor temperature. This indicates that heat loss has been minimised and the heating load has been significantly reduced. Additionally, the fact that the internal surface temperatures remain above the condensation limit prevents structural risks caused by moisture and indoor discomfort. Therefore, insulation applications compliant with the current TS825 standard provide significant benefits in terms of both energy efficiency and indoor thermal comfort.

The overall evaluation of the obtained temperature distribution graphs clearly reveals the effect of insulation on the thermal behaviour of building components. When all graphs are examined together, it is observed that sudden changes in the external ambient temperature are quickly transmitted to the internal surface in uninsulated scenarios. This effect is particularly striking in cities with severe winter conditions, such as Ardahan. For example, in Ardahan city under January conditions, in an uninsulated concrete structured roof (Figure 5.3), while the outdoor temperature dropped to -12°C, this effect reached the inner surface up to a depth of 150 mm without significant

development. However, in the insulated scenario according to the current TS825 standard (Figure 5.4), the internal surface temperature remained stable at around 19°C under the same external temperature conditions. Similarly, in a region with a hot climate like Antalya, in the uninsulated scenario (Figure 5.1), external surface temperatures approached 50°C during the summer months; however, when insulation was applied (Figure 5.2), this temperature increase remained confined to the surface layers and dissipated without reaching the internal surface temperature. This highlights the effect of insulation in ensuring indoor comfort under both summer and winter conditions.

When examining the temperature distribution graphs throughout the above material and the graphs provided in Appendix F, Figures F.1, F.2, F.3, and F.4: When comparing flat terrace roofs with concrete structure roofs, it can be seen that flat roofs have a sharper heat transfer gradient and are more sensitive to external conditions. In concrete roofs, due to the presence of thicker sections, the heat transfer process exhibits a broader distribution; however, the insulation effect is also clearly noticeable here.

In general, the graphs show how temperature changes vary within the material and the effect of the high temperature drop caused by insulation, thus providing a solid physical basis for the heat transfer rate calculations presented in the following sections.

The temperature distribution graphs analysed in detail in the main text are presented cross-referenced by month and roof type. However, to avoid repetition in the content, other graphs showing similar trends and representing different combinations of roof types are presented in Appendices F.1, F.2, F.3 and F.4. As other cities included in the study exhibited similar temperature gradients to those shown in the graphs in the main text, these data were not included in the thesis.

As a complementary part of the heat transfer analyses, the temporal variation of surface temperatures throughout the day was also examined. In this context, Figures 5.5 and 5.6 present data for January and July together, revealing the temporal variation of surface temperature differences in both summer and winter conditions. These graphs, prepared for two different roof types in the cities of Antalya and Ardahan, present a comparative analysis of the differences between internal surface temperatures and constant internal ambient temperatures over time.

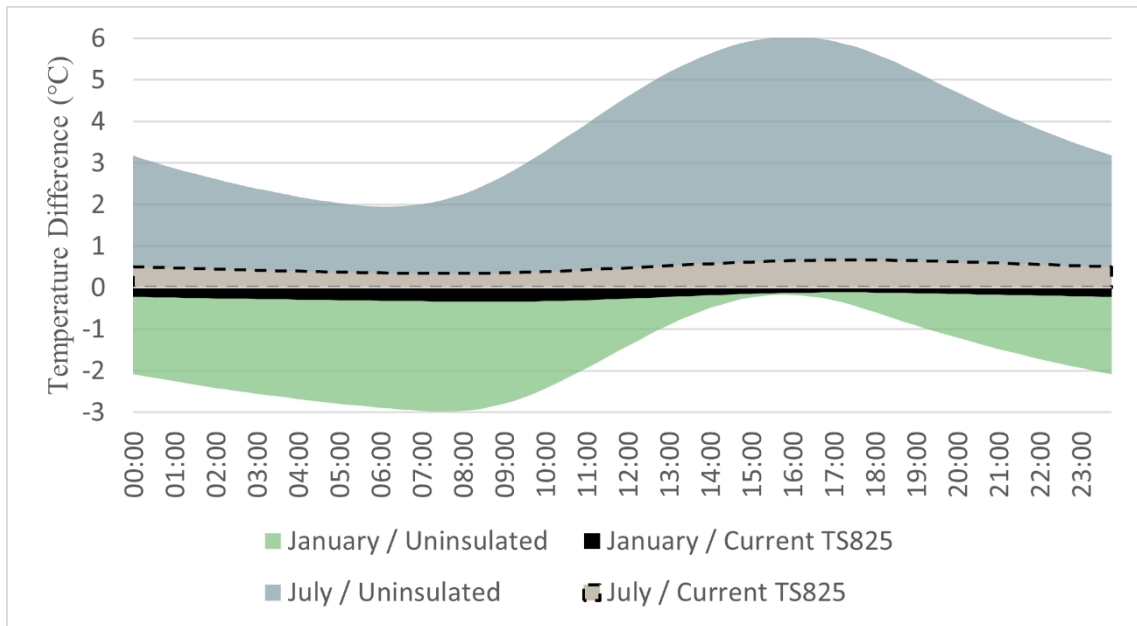


Figure 5.5. Diurnal variation of indoor surface temperature differences relative to indoor air temperature for insulated and uninsulated scenarios in Antalya, for concrete structure roof (January–July comparison)

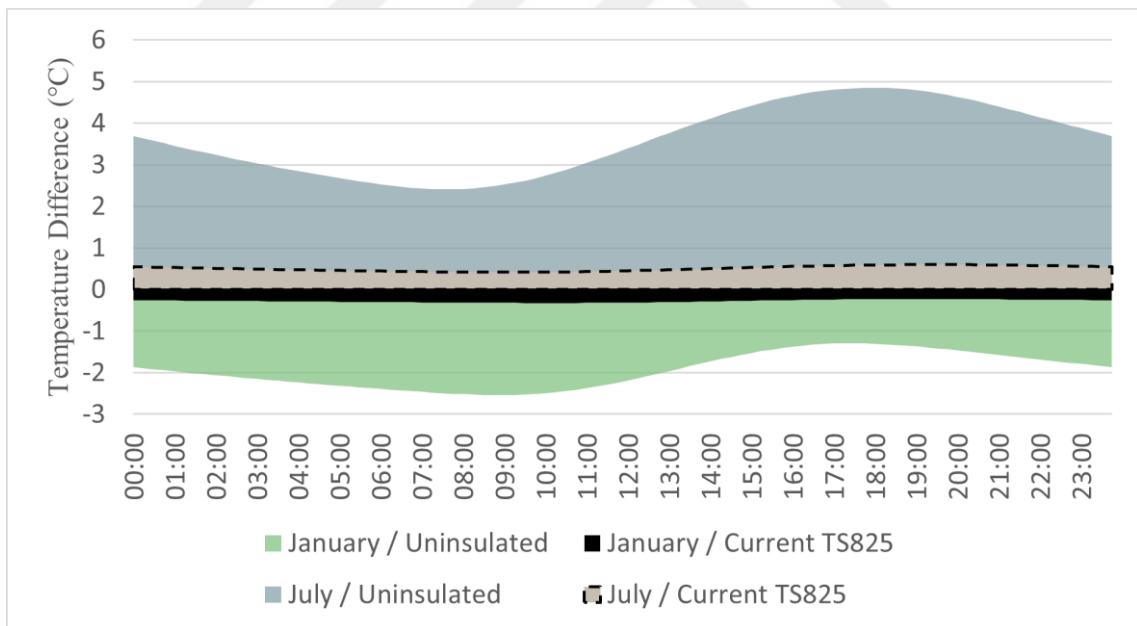


Figure 5.6. Diurnal variation of indoor surface temperature differences relative to indoor air temperature for insulated and uninsulated scenarios in Antalya, for flat terrace roof (January–July comparison)

Figure 5.5 shows a graph created for a concrete structure roof in Antalya province, indicating that in July, the internal surface temperature is approximately 6°C higher than

the internal ambient temperature at midday when no insulation is applied. When insulation compliant with current TS825 standards is applied, this difference drops to below approximately 0.5°C. In January, the internal surface temperature in an uninsulated condition is 2.5–3 °C below the internal ambient temperature; with insulation, this difference is reduced to almost negligible levels.

In Figure 5.6, similar trends are observed in the graph created for the flat terrace roof in Antalya, but in the uninsulated scenario, the internal surface temperature difference reaches 5.5–6 °C in July. In January, the difference is less pronounced, but insulation significantly reduces temperature fluctuations here as well. In both cases, the effect of insulation in reducing temperature differences is clearly demonstrated.

When both graphs are evaluated together, it is observed that indoor surface temperatures in Antalya show higher differences compared to indoor ambient temperatures in both summer and winter months in uninsulated scenarios. In particular, in July, the surface temperature significantly exceeds the indoor ambient temperature in uninsulated conditions, while in January, the surface temperature falls below the indoor ambient temperature. When insulation compliant with the current TS825 standard is applied, these differences are significantly reduced, and temperature fluctuations throughout the day are limited. This demonstrates that insulation not only limits heat loss or gain but also improves thermal comfort conditions by balancing interior surface temperatures. Additionally, the critical importance of insulation strategies in preventing the risk of condensation caused by low surface temperatures is once again confirmed.

Similar graphs obtained for Ardahan province were also created during the analysis process. However, since these graphs largely support the patterns observed in Antalya and do not present any new trends, they are presented in Appendix F.5 and Appendix F.6 to avoid repetition. These graphs show that insulation keeps the internal surface temperature closer to constant indoor conditions, especially in winter, thereby providing comprehensive validation of the findings.

Changes in surface temperature differences over time have revealed the extent to which interior surface conditions are protected from external environmental influences, depending on the roof type and insulation scenario. It is important for interior comfort that these differences remain below certain limits. However, the analysis of surface temperatures alone does not fully reflect the overall energy performance of roofs.

Therefore, in order to conduct a more comprehensive assessment of heat transfer, the total daily heat flux through the roof was compared across different insulation scenarios in the next phase. In this section, the daily total heat transfer ( $q$  values) per unit surface area obtained for each city was analysed in detail and visualised using bar graphs for flat terrace roofs (Figure 5.7, Figure 5.8) and radar graphs for concrete terrace roofs (Figure 5.11, Figure 5.12, Figure 5.13, Figure 5.14, etc.).

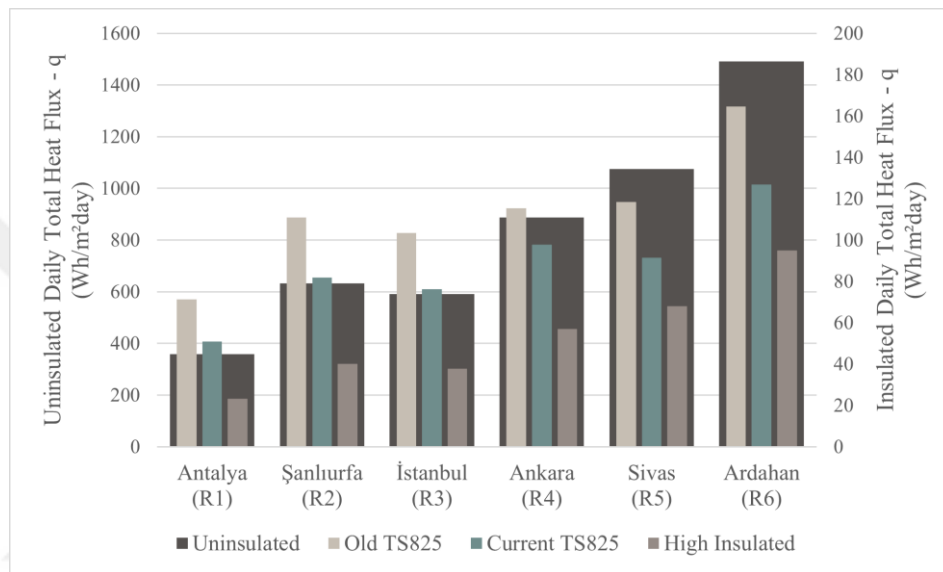


Figure 5.7. Daily Total Heat Flux ( $q$ ) Values for Flat Terrace Roofs Under Four Insulation Scenarios Across Six Cities in January Condition

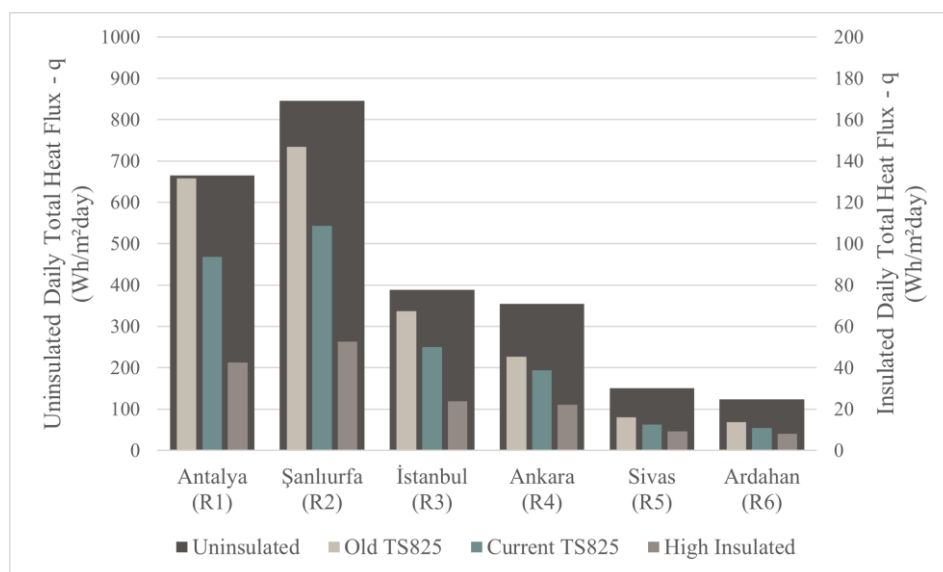


Figure 5.8. Daily Total Heat Flux ( $q$ ) Values for Flat Terrace Roofs Under Four Insulation Scenarios Across Six Cities in July Condition

The graphs in Figures 5.7 and 5.8, which show a comparative presentation of the daily total heat transfer for the unit surface area for January and July, provide an important insight into the effect of different insulation levels on heat transfer at the city level. In the graph for January, it is observed that the uninsulated condition significantly increases the  $q$  values, particularly in cold climate regions such as Ardahan, Sivas, and Ankara. Under January conditions, the  $q$  value for an uninsulated roof in Ardahan reaches 1491 Wh/m<sup>2</sup>·day, while the lowest value is 356 Wh/m<sup>2</sup>·day in Antalya. For Old TS825, Current TS825, and High Insulated, these ranges are 71-164, 51-127, and 23-95 Wh/m<sup>2</sup>·day, respectively. Based on these values, it is observed that each insulation improvement study results in a significant reduction in heat loss for flat terrace roofs in January. It is observed that Current TS825 provides approximately 23% energy savings compared to Old TS825, and approximately 42% in the high insulated scenario. The January values for flat terrace roofs demonstrate that the uninsulated condition is unacceptable in terms of energy performance, that the old TS825 falls short of providing adequate performance, that the current TS825 represents a significant step toward meeting global standards, and that heat loss can be minimised to an almost perfect degree under high insulation conditions.

Similarly, the graph for July shows that uninsulated conditions lead to significant heat gains in hot climate regions such as Antalya and Şanlıurfa. In Antalya and Şanlıurfa, which are located in hot climate regions,  $q$  values under uninsulated conditions range from 665 to 845 Wh/m<sup>2</sup>·day. In cities with continental climate characteristics such as Ankara, Sivas, and Ardahan, these values range from 124 to 354 Wh/m<sup>2</sup>·day. In the Old TS825, Current TS825, and High Insulated scenarios, where data for all cities are presented in a single range,  $q$  values remain within the ranges of 14–147, 11–109, and 8–53 Wh/m<sup>2</sup>·day, respectively. In Ankara, Sivas, and Ardahan, the cooling load in the Current TS825 and High Insulated insulation scenarios is observed to be as low as 8-38 Wh/m<sup>2</sup>·day, which is almost negligible.

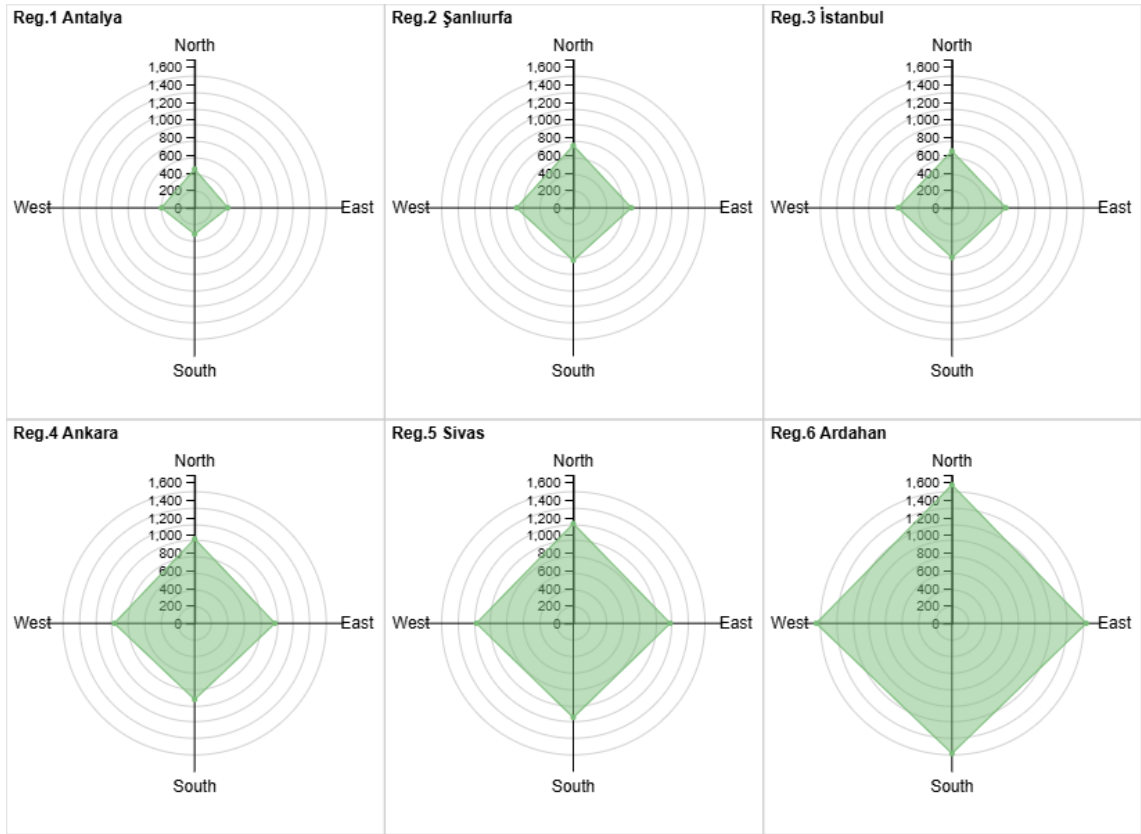


Figure 5.9. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof under the Uninsulated Scenario in January across Six Cities Representing Different Climate Regions in Türkiye

For concrete structure roofs, the uninsulated scenario shown in Figure 5.9 for January was examined. In this case, it was observed that quite high  $q$  values were obtained regardless of direction. This situation is particularly striking in continental climate regions under January conditions. In cities such as Ankara, Sivas, and Ardahan,  $q$  values on the north facade reach levels of 1018–1679  $\text{Wh/m}^2\cdot\text{day}$ , while on the south facade, these values differ significantly, remaining in the range of 924–1584  $\text{Wh/m}^2\cdot\text{day}$ . The fact that the values obtained in the south are approximately 95  $\text{Wh/m}^2\cdot\text{day}$  lower than those in the north demonstrates both how much the directional effect differs under continental climate conditions in uninsulated conditions and how important insulation is for reducing heating loads. Similar trends are observed in temperate regions such as İstanbul, Şanlıurfa, and Antalya, but the  $q$  values are lower, ranging from 324 to 756  $\text{Wh/m}^2\cdot\text{day}$ . In general, uninsulated buildings are exposed to significant heat loss under cold seasonal conditions, and in such cases, the effect of orientation on energy savings is approximately 8%.

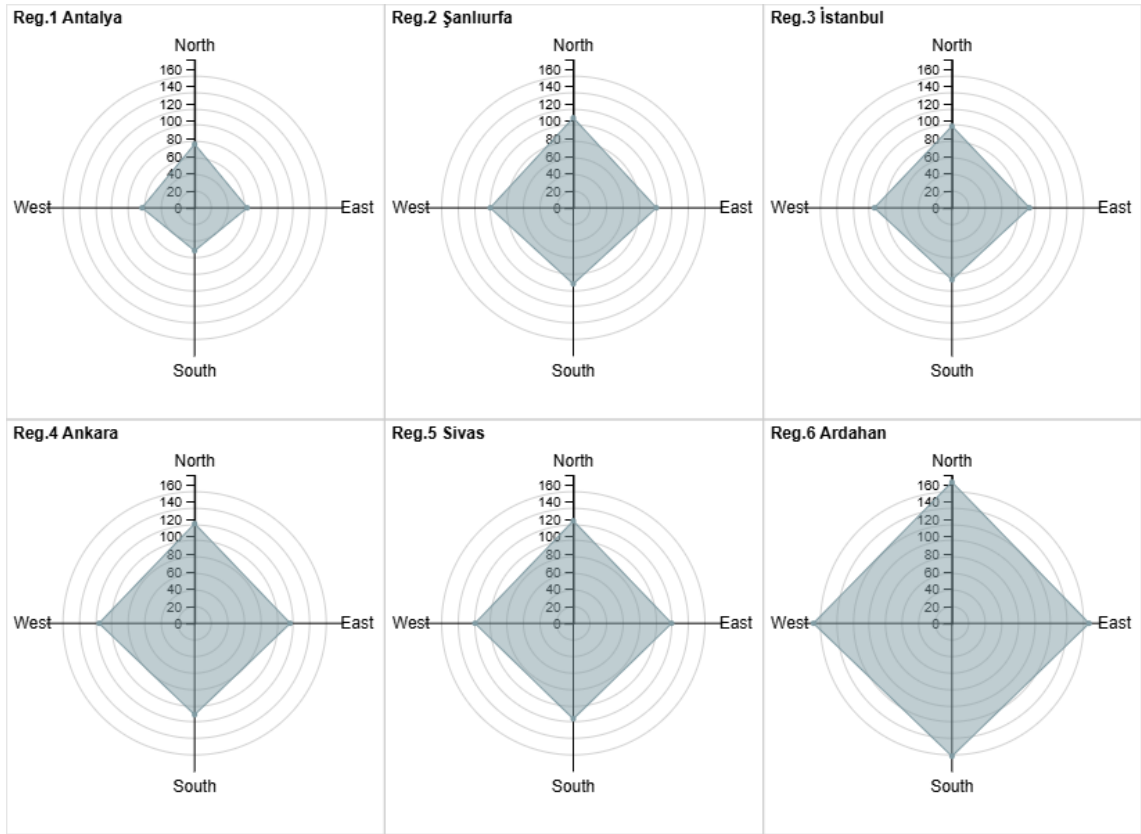


Figure 5.10. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof under the Old TS825 Scenario in January across Six Cities Representing Different Climate Regions in Türkiye

When examining the Old TS825 scenario shown in Figure 5.10 for concrete structure roofs in January, although there is a significant improvement compared to the uninsulated situation, it can be seen that it offers weaker performance than the current TS825 standard (Figure 5.13). Especially in continental regions such as Ankara, Sivas, and Ardahan,  $q$  values in the north are generally 3–12% higher than the current TS825 standard, while in the south, these values decrease to 53–164  $\text{Wh/m}^2\cdot\text{day}$  in all cities. This situation shows that the old standards provided sufficient protection in cold climates, but with the development of the standards, an average gain of 8% in heating loads has been achieved. In addition, it is seen that heat losses in the northern direction in continental climates are still at serious levels of 122–171  $\text{Wh/m}^2\cdot\text{day}$ . Parallel to the improvement in insulation, the heat loss advantage on south-facing facades continues in this scenario as well.

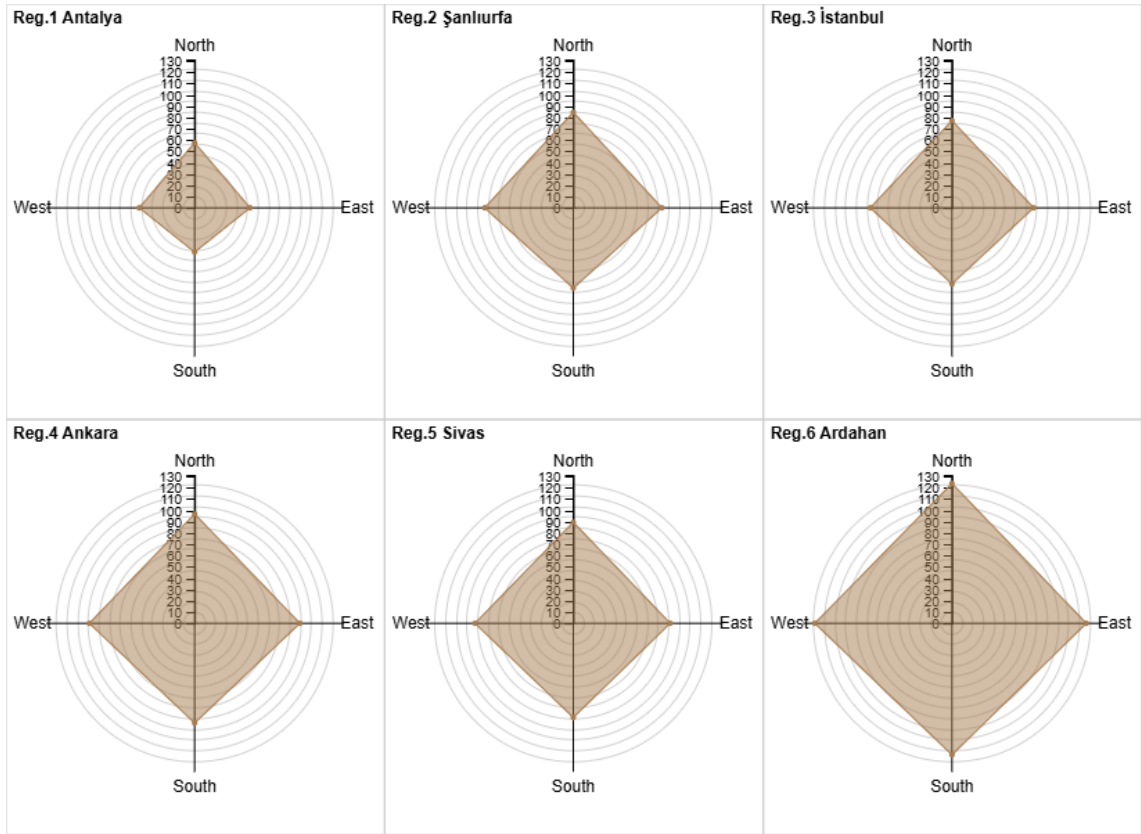


Figure 5.11. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof under the Current TS825 Scenario in January across Six Cities Representing Different Climate Regions in Türkiye

When examining the current TS825 insulation scenario shown in Figure 5.11 for concrete structure roofs in January, it can be seen that the  $q$  values obtained are significantly lower than those for uninsulated structures. In Ardahan, the  $q$  value for the north direction has decreased to  $131 \text{ Wh/m}^2\cdot\text{day}$ , indicating a reduction of approximately 92% compared to the uninsulated scenario. In other continental regions such as Sivas and Ankara, the values for the north direction are around  $95\text{--}103 \text{ Wh/m}^2\cdot\text{day}$ , while those for the south direction are in the range of  $89\text{--}94 \text{ Wh/m}^2\cdot\text{day}$ . Although the directional difference is still observable, it has decreased significantly compared to previous scenarios. This indicates that current standards provide sufficient performance to enhance energy efficiency even in cold climates and that north-facing heat losses can be controlled. Additionally, the advantage provided by the south-facing orientation continues in this scenario, though the difference has narrowed.

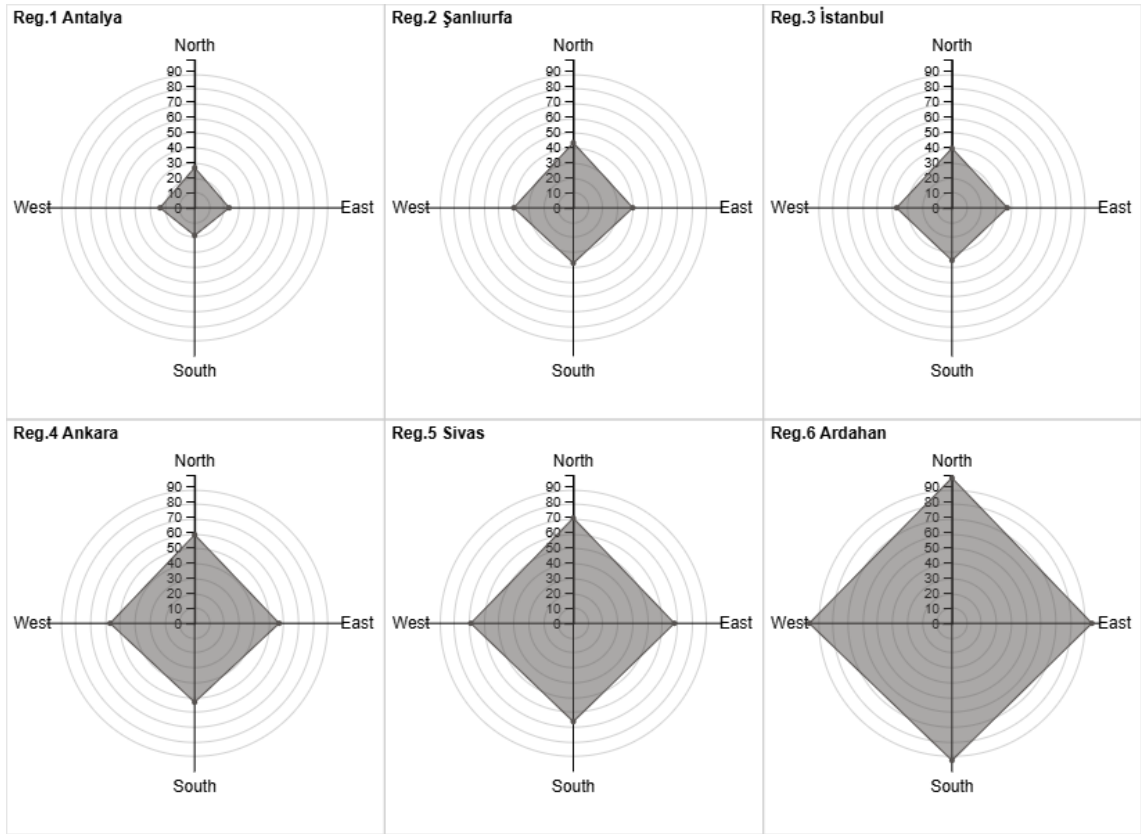


Figure 5.12. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof Under High Insulated Scenario in January across Six Cities Representing Different Climate Regions in Türkiye

When examining the high insulation scenario shown in Figure 5.12 for concrete structure roofs in January,  $q$  values have fallen to minimum levels in all regions. In continental regions with high heat loss potential, such as Ardahan, Sivas, and Ankara, heat losses are measured at very low levels of 59–98  $\text{Wh/m}^2\cdot\text{day}$  on the north facade and 54–92  $\text{Wh/m}^2\cdot\text{day}$  on the south facade. In temperate regions such as İstanbul, Şanlıurfa, and Antalya, these values are even lower, ranging from 19 to 44  $\text{Wh/m}^2\cdot\text{day}$ . The directional difference has reached its lowest level in this scenario, with the  $q$  value difference between the north and south directions decreasing to 4–10  $\text{Wh/m}^2\cdot\text{day}$ . This situation demonstrates that high-quality insulation not only minimises energy losses but also balances direction-dependent heat transfer differences and provides homogeneous thermal performance depending on the direction. As a result, this scenario represents the most effective form of passive energy conservation achieved through insulation methods.

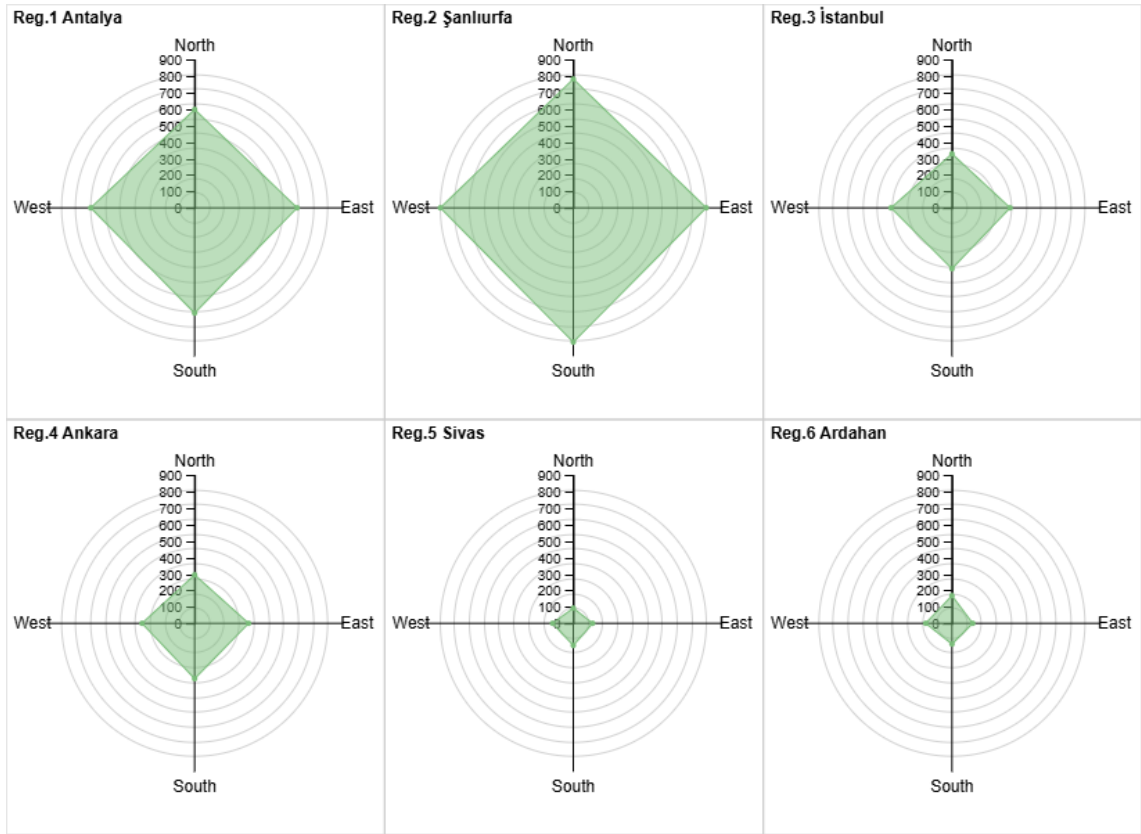


Figure 5.13. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof Under the Uninsulated Scenario in July across Six Cities Representing Different Climate Regions in Türkiye

When examining the uninsulated scenario shown in Figure 5.13 for concrete structure roofs in July, it can be seen that heat gains reach particularly high values in the south, east and west directions in Şanlıurfa and Antalya, which are hot climate regions. In these cities,  $q$  values reach levels of 692–904  $\text{Wh/m}^2\cdot\text{day}$  in the south, east, and west directions, while in the north direction, these values remain in the range of 667–863  $\text{Wh/m}^2\cdot\text{day}$ . In continental climate regions such as Ankara, Sivas, and Ardahan, the values are lower, but the effect of directional differences is still noticeable. Maximum gains are observed in the south, where solar radiation is more direct, and it is understood that this orientation becomes disadvantageous for buildings in summer conditions. This scenario clearly demonstrates that insufficient insulation in summer months imposes a high heat load on interior spaces.

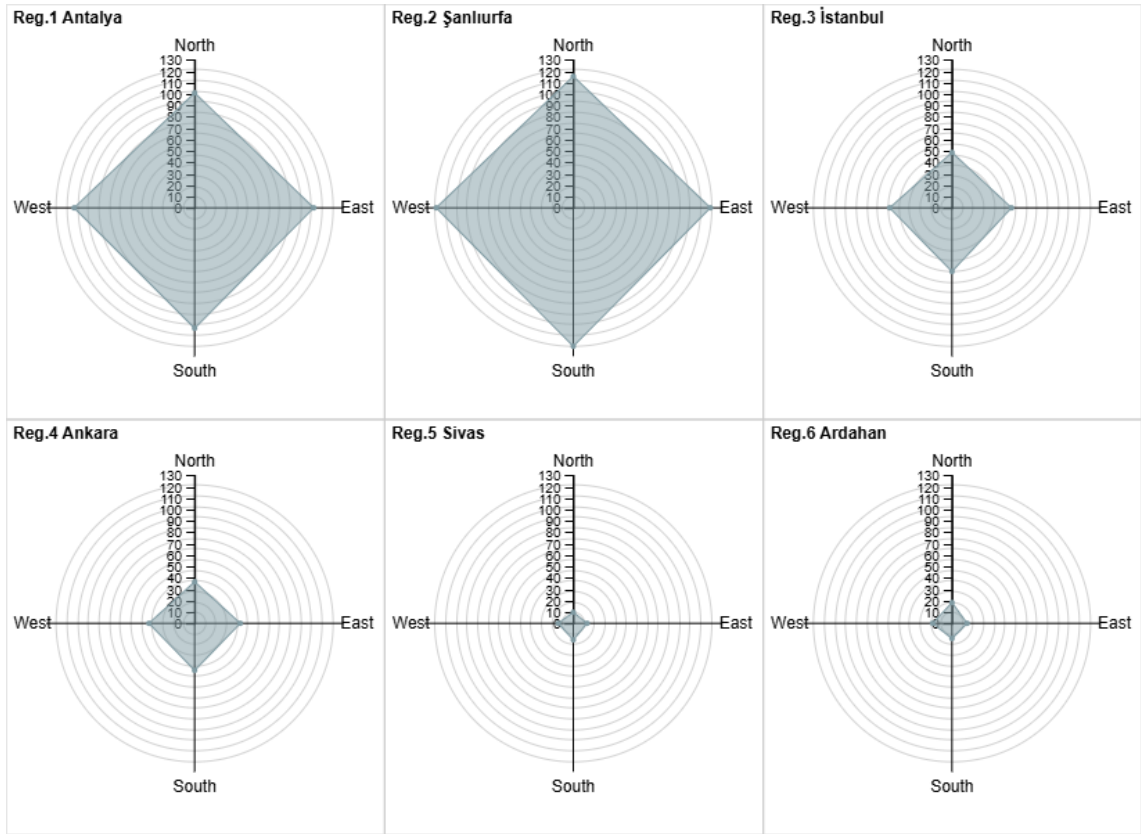


Figure 5.14. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof Under the Old TS825 Scenario in July across Six Cities Representing Different Climate Regions in Türkiye

When examining the old TS825 insulation scenario shown in Figure 5.14 for concrete structure roofs in July, although there is a significant decrease in  $q$  values compared to the uninsulated situation, heat gains on the south facade remain high, especially in hot regions. In Antalya and Şanlıurfa,  $q$  values of 114–131  $\text{Wh/m}^2\cdot\text{day}$  are observed for the south direction, while the north direction drops to levels of 108–125  $\text{Wh/m}^2\cdot\text{day}$ . Although these values indicate a reduction of up to 85% compared to the uninsulated scenario, the directional differences remain pronounced. In continental regions such as Ankara, Sivas, and Ardahan, values are observed to drop to the 10–45  $\text{Wh/m}^2\cdot\text{day}$  range. When the outdoor conditions of Ardahan and Sivas provinces are examined, it is clearly foreseeable that the cooling load would be this low. This situation confirms the section in the TS825 standard that states that cooling load calculations should not be performed. This scenario demonstrates that the old standards could not establish an adequate solar radiation barrier for the summer season and that excessive heat gains, particularly in the southern direction, persist.

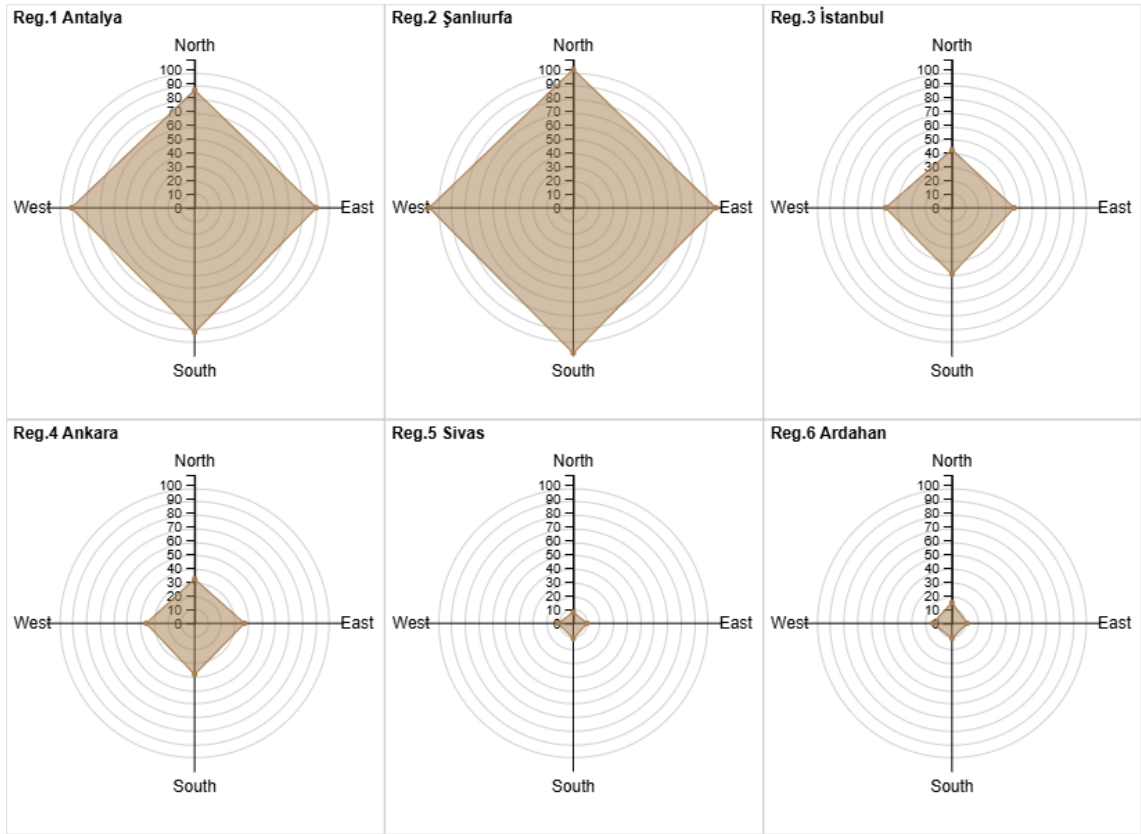


Figure 5.15. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof Under the Current TS825 Scenario in July across Six Cities Representing Different Climate Regions in Türkiye

When examining the current TS825 insulation scenario shown in Figure 5.15 for concrete structure roofs in July, even in regions with high solar radiation potential such as Antalya and Şanlıurfa, the maximum values in the south direction range around 92–108  $\text{Wh/m}^2\cdot\text{day}$ , while the north-facing side drops to levels of 87–103  $\text{Wh/m}^2\cdot\text{day}$ . In cooler regions such as Ankara, Sivas, and Ardahan,  $q$  values remain within the range of 8–38  $\text{Wh/m}^2\cdot\text{day}$  in all directions. In this scenario, the effect of insulation has reduced directional differences and enabled heat gains to be controlled. The current TS825 standard has been found to offer functional performance in reducing solar energy loads during the summer months.

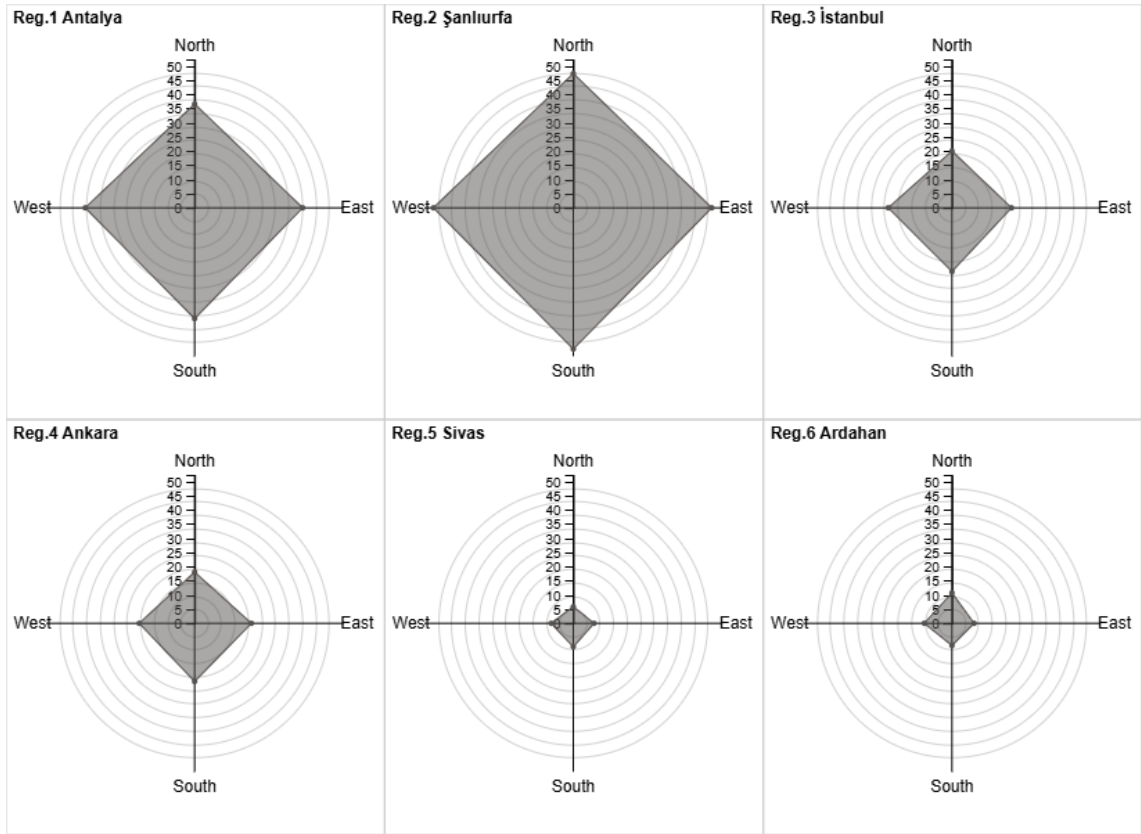


Figure 5.16. Orientation-Based Daily Total Heat Flux ( $q$  in  $\text{Wh/m}^2\cdot\text{day}$ ) for Concrete Structure Roof Under the High Insulated Scenario in July across Six Cities Representing Different Climate Regions in Türkiye

When examining the high insulation scenario shown in Figure 5.16 for concrete structure roofs in July,  $q$  values have fallen to their lowest levels in all regions. Even in hot regions such as Şanlıurfa and Antalya,  $q$  values for the south direction remain within the 41–52  $\text{Wh/m}^2\cdot\text{day}$  range, while for the north direction, they drop to 39–50  $\text{Wh/m}^2\cdot\text{day}$  levels. In continental climates such as Ankara, Sivas, and Ardahan,  $q$  values have decreased to the range of 6–22  $\text{Wh/m}^2\cdot\text{day}$  in all directions, and directional differences have become almost negligible. This scenario clearly demonstrates that high-performance insulation not only minimises total heat gains during summer months but also reduces direction-dependent asymmetric load distribution. Thus, a homogeneous and controlled thermal environment is provided indoors.

Heat transfer is significantly influenced by roof type, insulation, orientation, location and season, highlighting the importance of informed insulation choices. Tables 5.1 and 5.2 present the  $q$  values for all scenarios in January and July, respectively.

Table 5.1. q-values (Wh/m<sup>2</sup>·day) for All Roof, Orientation, and Insulation Scenarios in January for Six Climatic Regions of Türkiye

| Roof Type - Orientation |       | Reg.1 Antalya |           |               |                | Reg.2 Şanlıurfa |           |               |                |
|-------------------------|-------|---------------|-----------|---------------|----------------|-----------------|-----------|---------------|----------------|
|                         |       | Uninsulated   | Old TS825 | Current TS825 | High Insulated | Uninsulated     | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 358.85        | 71.37     | 50.90         | 23.13          | 632.48          | 110.86    | 81.76         | 40.10          |
| Concrete Structure      | North | 472.94        | 76.75     | 61.91         | 27.43          | 756.27          | 109.65    | 90.33         | 44.00          |
|                         | East  | 397.79        | 64.49     | 52.06         | 23.05          | 697.49          | 101.11    | 83.29         | 40.57          |
|                         | South | 323.96        | 52.57     | 42.40         | 18.74          | 636.37          | 92.25     | 75.98         | 36.91          |
|                         | West  | 398.27        | 64.57     | 52.13         | 23.08          | 696.30          | 100.95    | 83.15         | 40.39          |

| Roof Type - Orientation |       | Reg.3 İstanbul |           |               |                | Reg.4 Ankara |           |               |                |
|-------------------------|-------|----------------|-----------|---------------|----------------|--------------|-----------|---------------|----------------|
|                         |       | Uninsulated    | Old TS825 | Current TS825 | High Insulated | Uninsulated  | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 589.74         | 103.37    | 76.23         | 37.71          | 886.42       | 115.24    | 97.68         | 56.97          |
| Concrete Structure      | North | 685.27         | 99.36     | 81.85         | 39.78          | 1018.29      | 121.67    | 103.44        | 59.37          |
|                         | East  | 649.07         | 94.10     | 77.52         | 37.77          | 973.22       | 116.41    | 98.89         | 56.51          |
|                         | South | 606.46         | 87.92     | 72.42         | 35.28          | 923.73       | 110.48    | 93.85         | 53.62          |
|                         | West  | 648.39         | 93.94     | 77.40         | 37.63          | 973.35       | 116.27    | 98.90         | 56.75          |

| Roof Type - Orientation |       | Reg.5 Sivas |           |               |                | Reg.6 Ardahan |           |               |                |
|-------------------------|-------|-------------|-----------|---------------|----------------|---------------|-----------|---------------|----------------|
|                         |       | Uninsulated | Old TS825 | Current TS825 | High Insulated | Uninsulated   | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 1073.73     | 118.34    | 91.36         | 67.97          | 1491.11       | 164.45    | 126.80        | 94.82          |
| Concrete Structure      | North | 1217.41     | 123.71    | 95.25         | 70.70          | 1678.74       | 171.00    | 131.40        | 97.68          |
|                         | East  | 1176.37     | 119.57    | 92.02         | 68.30          | 1627.13       | 165.50    | 127.34        | 94.62          |
|                         | South | 1134.80     | 115.28    | 88.76         | 65.88          | 1584.23       | 161.35    | 124.01        | 92.15          |
|                         | West  | 1181.15     | 120.06    | 92.40         | 68.61          | 1645.33       | 167.36    | 128.77        | 95.73          |

Table 5.2. q-values (Wh/m<sup>2</sup>·day) for All Roof, Orientation, and Insulation Scenarios in July for Six Climatic Regions of Türkiye

| Roof Type - Orientation |       | Reg.1 Antalya |           |               |                | Reg.2 Şanlıurfa |           |               |                |
|-------------------------|-------|---------------|-----------|---------------|----------------|-----------------|-----------|---------------|----------------|
|                         |       | Uninsulated   | Old TS825 | Current TS825 | High Insulated | Uninsulated     | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 664.90        | 131.65    | 93.55         | 42.63          | 845.46          | 146.96    | 108.56        | 52.70          |
| Concrete Structure      | North | 666.85        | 107.95    | 87.09         | 38.73          | 863.15          | 124.59    | 102.69        | 49.91          |
|                         | East  | 691.89        | 112.00    | 90.34         | 40.18          | 891.49          | 128.76    | 106.09        | 51.55          |
|                         | South | 705.25        | 114.15    | 92.03         | 40.95          | 903.90          | 130.53    | 107.52        | 52.26          |
|                         | West  | 701.66        | 113.55    | 91.55         | 40.73          | 898.17          | 129.69    | 106.81        | 52.00          |

| Roof Type - Orientation |       | Reg.3 İstanbul |           |               |                | Reg.4 Ankara |           |               |                |
|-------------------------|-------|----------------|-----------|---------------|----------------|--------------|-----------|---------------|----------------|
|                         |       | Uninsulated    | Old TS825 | Current TS825 | High Insulated | Uninsulated  | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 388.11         | 67.47     | 49.91         | 23.75          | 354.30       | 45.43     | 38.71         | 22.07          |
| Concrete Structure      | North | 363.42         | 52.58     | 43.28         | 21.08          | 323.85       | 38.57     | 32.83         | 18.79          |
|                         | East  | 387.83         | 56.07     | 46.18         | 22.29          | 361.54       | 43.05     | 36.59         | 20.98          |
|                         | South | 414.49         | 59.94     | 49.34         | 23.79          | 373.97       | 44.54     | 37.83         | 21.68          |
|                         | West  | 409.96         | 59.26     | 48.78         | 23.49          | 356.58       | 42.46     | 36.11         | 20.66          |

| Roof Type - Orientation |       | Reg.5 Sivas |           |               |                | Reg.6 Ardahan |           |               |                |
|-------------------------|-------|-------------|-----------|---------------|----------------|---------------|-----------|---------------|----------------|
|                         |       | Uninsulated | Old TS825 | Current TS825 | High Insulated | Uninsulated   | Old TS825 | Current TS825 | High Insulated |
| Flat Terrace            |       | 151.03      | 16.08     | 12.53         | 9.35           | 123.98        | 13.78     | 10.76         | 7.96           |
| Concrete Structure      | North | 102.52      | 10.35     | 8.00          | 5.91           | 190.87        | 19.36     | 14.89         | 11.07          |
|                         | East  | 133.53      | 13.59     | 10.42         | 7.71           | 141.56        | 14.11     | 10.98         | 8.21           |
|                         | South | 150.46      | 15.19     | 11.72         | 8.68           | 142.26        | 14.44     | 11.10         | 8.26           |
|                         | West  | 140.69      | 14.18     | 10.95         | 8.11           | 180.98        | 18.37     | 14.06         | 10.51          |

## CHAPTER 6

### CONCLUSIONS AND FUTURE DIRECTIONS

This study has revealed in detail the heat transfer processes occurring in building roofs through numerical analyses conducted in six cities representing different climate zones in Türkiye, within the scope of two different roof typologies and four different insulation scenarios. The analyses conducted have shown that the level of thermal insulation and the type of roof have significant effects on surface temperatures and total heat transfer quantities. Particularly in uninsulated scenarios, changes in external ambient temperatures are quickly and effectively reflected on the internal surfaces of the structure. In contrast, in insulation scenarios compliant with old TS825<sup>14</sup>, current TS825<sup>15</sup> and European Union standards<sup>16</sup>, heat transfer is suppressed at high rates of 86.04%, 89.09%, and 93.90%, respectively.

The transient analysis method employed in the study enabled the evaluation of the effects of time-dependent boundary conditions, such as outdoor temperature, operative sky temperature calculated based on relative humidity and solar radiation, on heat transfer in a more realistic manner. This approach revealed the limitations of methods based on constant boundary conditions. A comparison of results has indicated that standard calculations based on the TS825 protocol may be inadequate in meeting contemporary energy efficiency targets, particularly in relation to the failure to account for temporal variations over brief periods.

The thesis examined the heat transfer rates for flat terrace roof and concrete structure roof typologies, demonstrating significant variability depending on city, season, and insulation scenario. In January, within continental climate regions, particularly in Ankara, Sivas, and Ardahan,  $q$  values for the concrete structure roof ranged from 1018 to 1679 Wh/m<sup>2</sup>·day in the uninsulated scenario. In the south, these values diminished to 924–1584 Wh/m<sup>2</sup>·day, leading to a direction-dependent  $q$  value difference of approximately 95 Wh/m<sup>2</sup>·day. For flat terrace roofs, these values reach up to 886–1491 Wh/m<sup>2</sup>·day, indicating that uninsulated structures are highly vulnerable to energy losses.

The investigation established that the old TS825 scenario reduced  $q$  values to a limited extent in both roof types. For concrete structure roofs, the south orientation ranged from 53 to 161 Wh/m<sup>2</sup>·day, while the north orientation ranged from 77 to 171 Wh/m<sup>2</sup>·day. For the flat terrace roof, values ranging from 71 to 164 Wh/m<sup>2</sup>·day were recorded in January. The findings of this study indicate an 8% higher energy loss in comparison with the current TS825 standard, thereby underscoring the inadequacy of the former TS825 standard.

In the current TS825 scenario, a significant decrease in  $q$  values has been observed for both roof types; the  $q$  values for flat terrace roofs have been calculated to range between 51-127 Wh/m<sup>2</sup>·day. For the concrete structure roof, the south orientation was measured at 42-124 Wh/m<sup>2</sup>·day, while the north orientation was measured at 62-131 Wh/m<sup>2</sup>·day. In this case, directional differences have decreased significantly in cities with continental climate conditions, such as Ankara, Sivas, and Ardahan. Meanwhile, directional differences have shown a tendency to increase relatively in cities with temperate climate conditions. Indoor environmental conditions have been shown to be more balanced in both roof types.

The High Insulated scenario yielded the lowest  $q$  values among all scenarios for both January and July. For flat terrace roof in January, values ranged from 23 to 95 Wh/m<sup>2</sup>·day. For concrete structured roof, values ranged from 59-98 Wh/m<sup>2</sup>·day for the northern side and 54-92 Wh/m<sup>2</sup>·day for the southern side in continental cities, and from 19-44 Wh/m<sup>2</sup>·day in temperate regions. Directional differences decreased to low levels of 4-10 Wh/m<sup>2</sup>·day.

In July, the  $q$  values for flat terrace roofs ranged from 388 to 845 Wh/m<sup>2</sup>·day in hot climate cities such as Antalya, Şanlıurfa and Istanbul in the uninsulated scenario, while in continental regions these values remained in the range of 124 to 354 Wh/m<sup>2</sup>·day. In the old TS825 scenario, these values ranged from 67-147 Wh/m<sup>2</sup>·day in hot climates and remained between 14-45 Wh/m<sup>2</sup>·day in continental climates. In the current TS825 scenario, these values range from 50-109 Wh/m<sup>2</sup>·day in warm climates and 11-39 Wh/m<sup>2</sup>·day in continental climates. In the context of the High Insulated scenario, the range has been observed to decrease to 24-43 Wh/m<sup>2</sup>·day in warm climates and 8-22 Wh/m<sup>2</sup>·day in continental climates.

In July, the  $q$  values for concrete structure roofs ranged from 414 to 904 Wh/m<sup>2</sup>·day for south-facing roofs and from 363 to 863 Wh/m<sup>2</sup>·day for north-facing roofs in uninsulated scenarios under hot climate conditions. In the old TS825 scenario under hot climate conditions,  $q$  values for south-facing roofs range from 60 to 131 Wh/m<sup>2</sup>·day, while for north-facing roofs they range from 53 to 125 Wh/m<sup>2</sup>·day. In the context of the current TS825 scenario, the  $q$  values for south-facing orientations range from 49 to 108 Wh/m<sup>2</sup>·day, while for north-facing orientations, they range from 43 to 103 Wh/m<sup>2</sup>·day. For High Insulated;  $q$  values for south-facing orientations are calculated to be in the range of 24-52 Wh/m<sup>2</sup>·day, and for north-facing orientations, they are in the range of 21-50 Wh/m<sup>2</sup>·day.

In summary, the analyses conducted revealed that both heat losses in winter and heat gains in summer decreased significantly with increased insulation levels. In January, under continental climate conditions,  $q$  values for flat terrace roofs in uninsulated scenarios ranged from 886 to 1491 Wh/m<sup>2</sup>·day, while for concrete structure roofs they ranged from 924 to 1679 Wh/m<sup>2</sup>·day. In the current high-insulation scenario, these values have decreased below 100 Wh/m<sup>2</sup>·day for both roof types. In July, under conditions of hot climate,  $q$  values for flat terrace roofs reach 845 Wh/m<sup>2</sup>·day and for concrete structure roofs 904 Wh/m<sup>2</sup>·day. In the high insulation scenario, these values decrease to 43 and 52 Wh/m<sup>2</sup>·day, respectively. The findings indicate that enhancing the insulation level can result in energy savings of up to 80–90%, while also mitigating both orientation-dependent imbalances and sudden temperature transitions.

When evaluated in terms of directional differences, the north side is identified as the facade with the highest heat loss in all scenarios, while the south side is identified as the facade with the highest heat gain. In scenarios where high levels of insulation are employed, this difference is reduced to 4–10 Wh/m<sup>2</sup>·day, thereby ensuring indoor thermal stability. According to calculations made in accordance with the current TS825 standard used in Türkiye, an improvement of approximately 4–10% in heat loss and gain has been observed compared to the old TS825 standard. Furthermore, analysis demonstrates that the  $q$  values of the east and west directions are analogous to those of the south direction in the majority of scenarios, with the discrepancy between them generally ranging from 0.1–5%.

The findings reached at this point are important in that they show that similar trends continue in different scenarios, without being limited to a specific building type or seasonal conditions. The increase in insulation levels reduces energy demand throughout the year, reduces the load on HVAC systems, and increases user comfort. Additionally, the fact that existing standards such as TS825 are insensitive to fluctuations over short time intervals has once again highlighted the necessity of transient analyses in energy performance calculations.

Future studies can be expanded based on the findings of this thesis. In particular, analysing east-west orientation differences using higher-resolution regional models will contribute to the development of orientation-sensitive passive design strategies. Beyond the two roof typologies examined in this study, it is recommended that the structural diversity of roof systems be taken into account and that different roof types be analysed in terms of time-dependent heat transfer using similar methods in the future. In particular, the evaluation of passive strategies such as phase change materials (PCM), reflective coatings, green roof systems, and cold surface applications within this scope could provide new contributions to sustainability-focused design approaches. However, the use of meteorological data sets compatible with climate change scenarios and regional, long-term observation data will enhance the accuracy of energy simulations and strengthen the validity of the findings.

Ultimately, this thesis has comprehensively demonstrated not only the direct effects of existing insulation systems on energy, but also the role of orientation sensitivity and temporal variability on performance. The findings are expected to provide an important scientific and practical reference for the widespread adoption of energy-efficient building design, the updating of national insulation standards, and the promotion of sustainable architectural decisions.

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## APPENDICES

### APPENDIX A

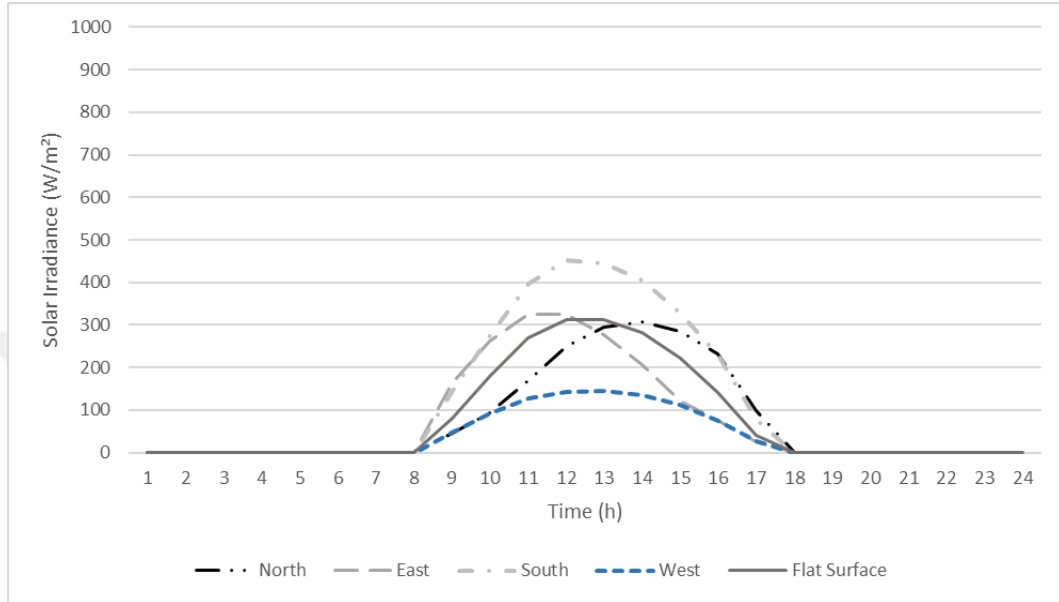


Figure A1. Monthly Averaged Daily Data of Solar Radiation in Ankara at January (Orientations Were Given for  $30^\circ$  Angle)

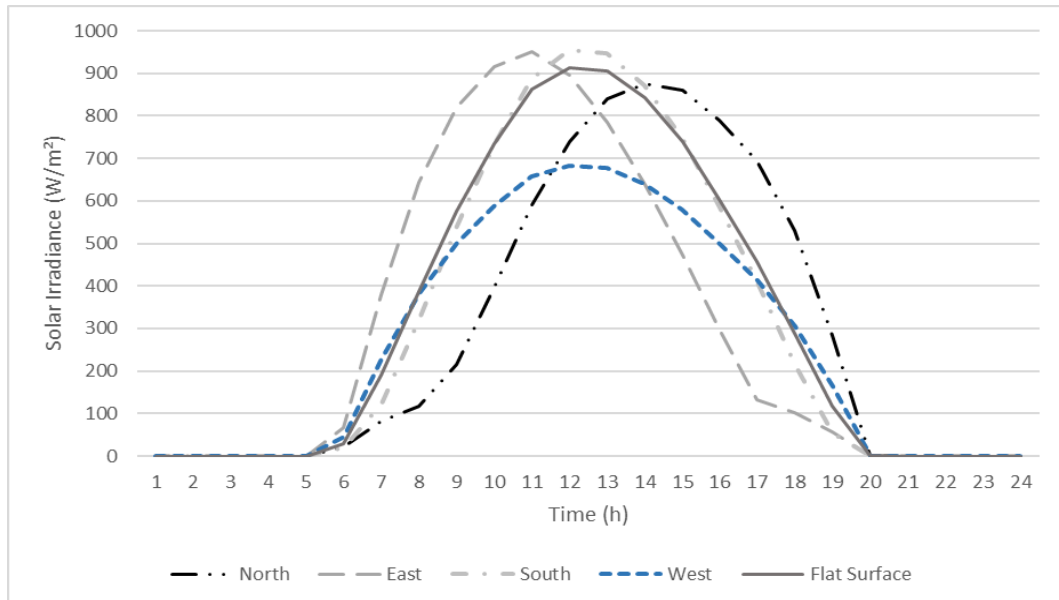


Figure A2. Monthly Averaged Daily Data of Solar Radiation in Ankara at July (Orientations Were Given for  $30^\circ$  Angle)

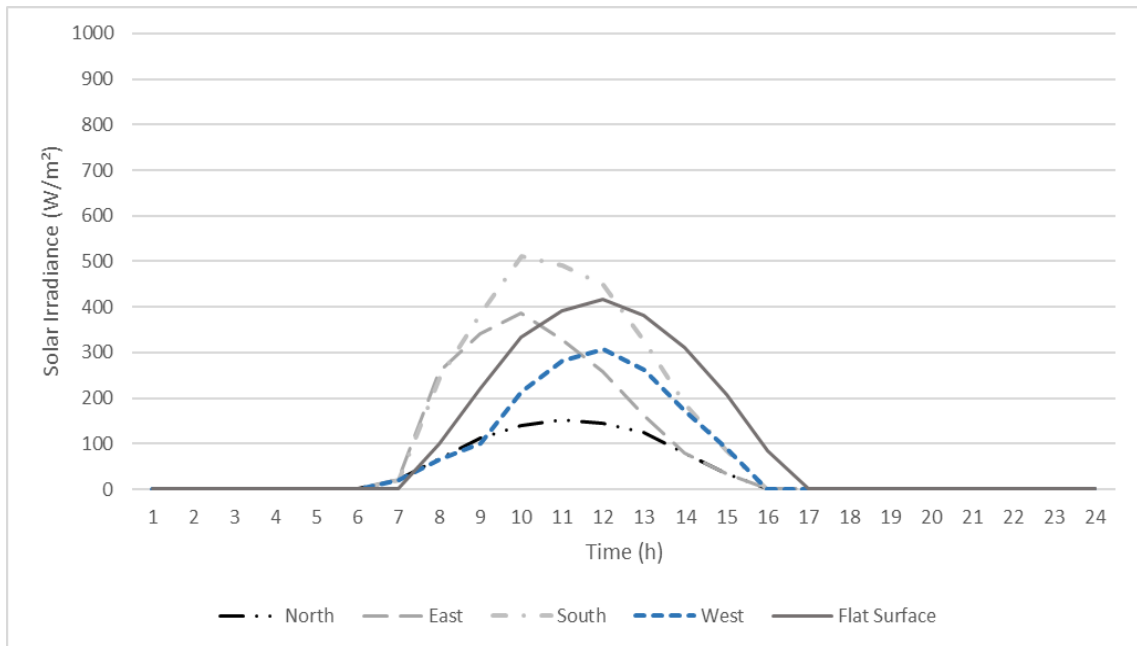


Figure A3. Monthly Averaged Daily Data of Solar Radiation in Ardahan at January  
(Orientations Were Given for 30° Angle)

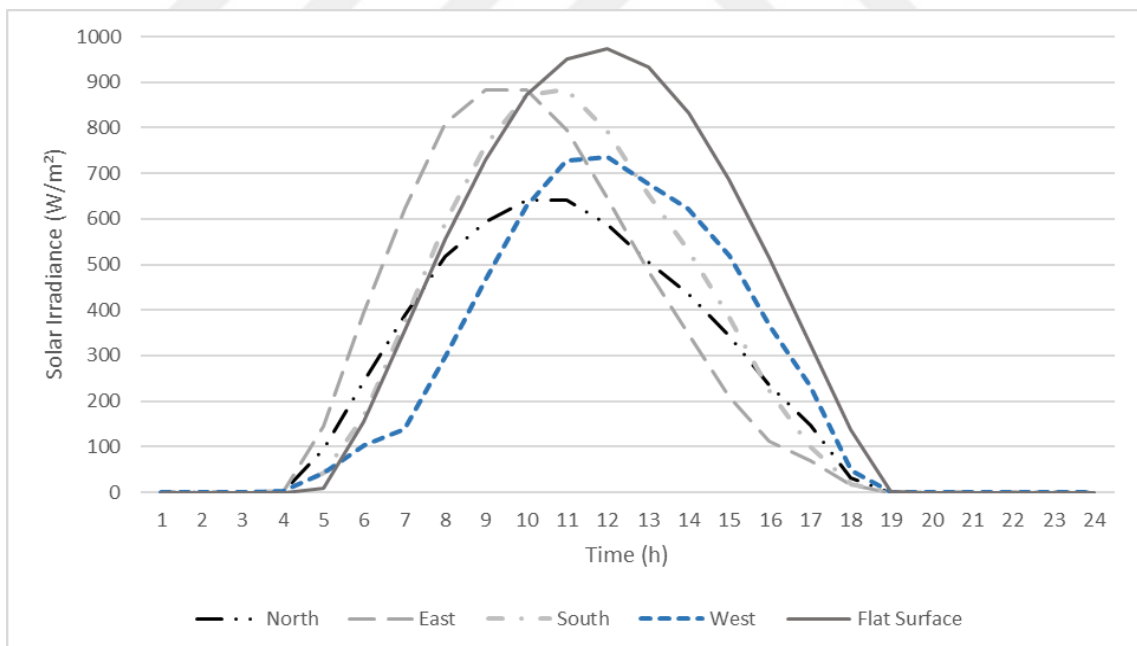


Figure A4. Monthly Averaged Daily Data of Solar Radiation in Ardahan at July  
(Orientations Were Given for 30° Angle)

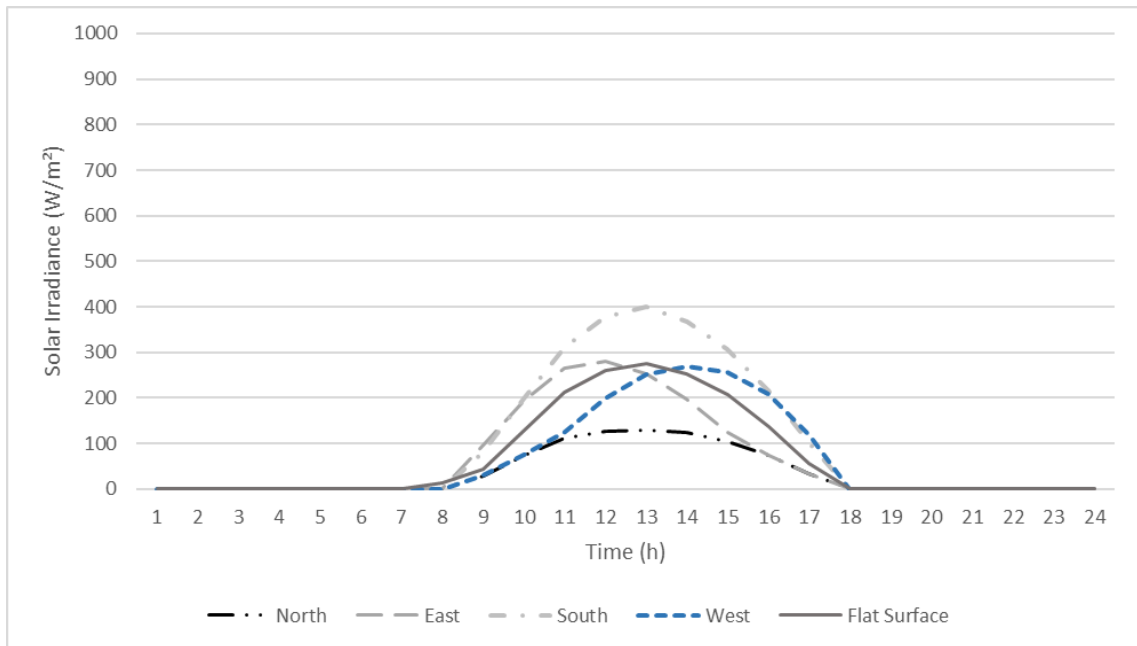


Figure A5. Monthly Averaged Daily Data of Solar Radiation in İstanbul at January  
(Orientations Were Given for 30° Angle)

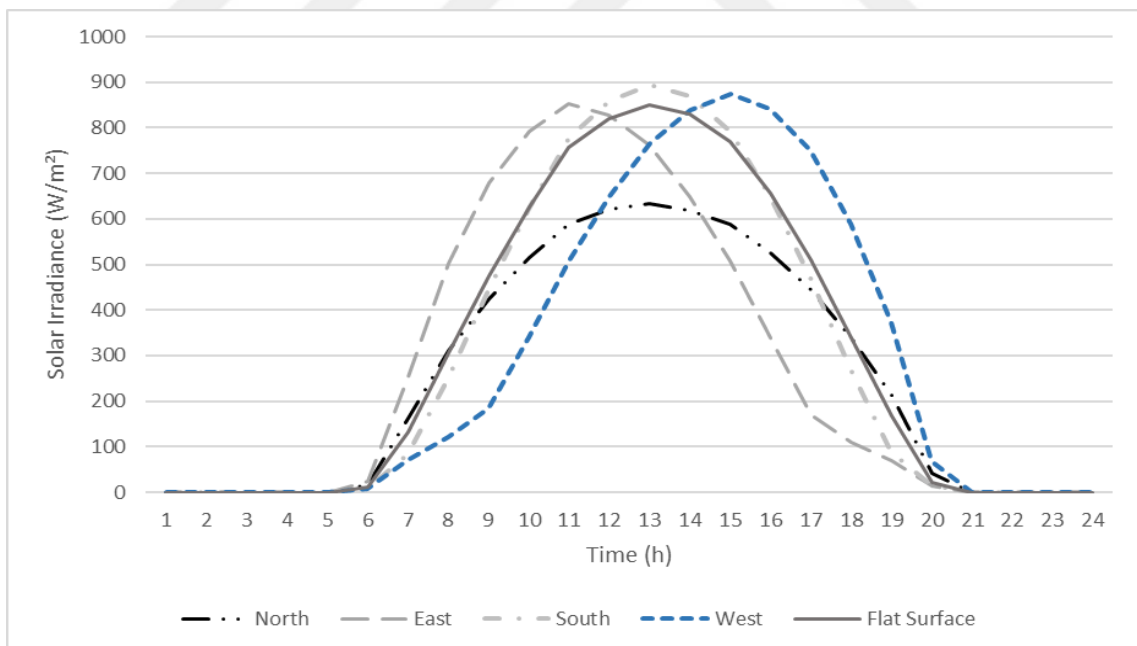


Figure A6. Monthly Averaged Daily Data of Solar Radiation in İstanbul at July  
(Orientations Were Given for 30° Angle)

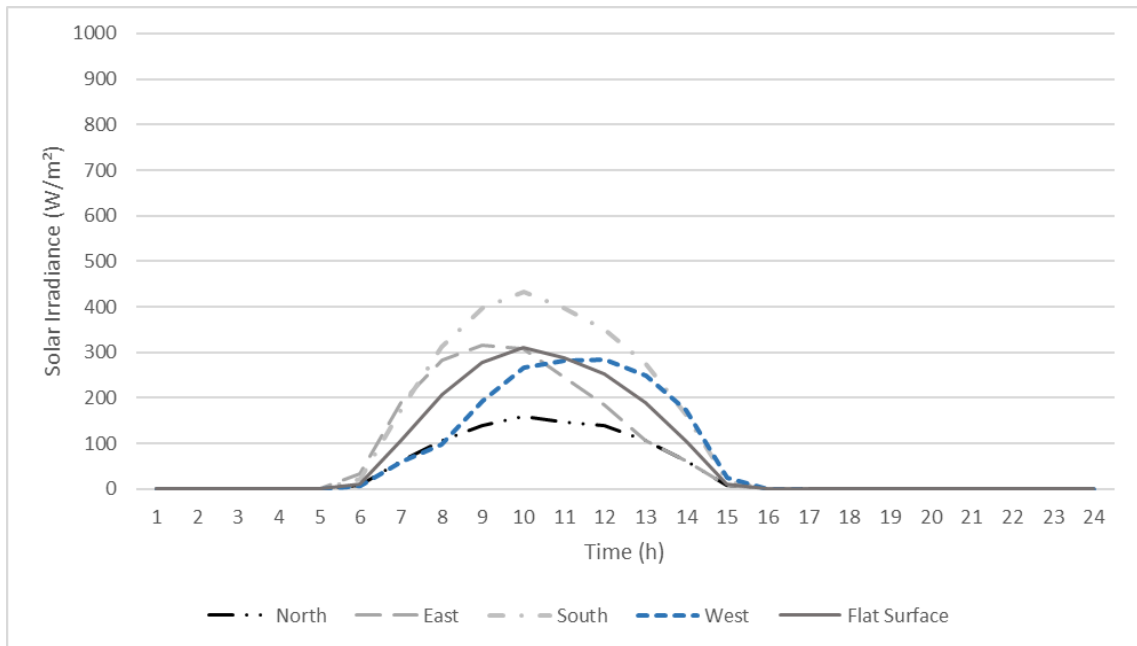


Figure A7. Monthly Averaged Daily Data of Solar Radiation in Sivas at January (Orientations Were Given for 30° Angle)

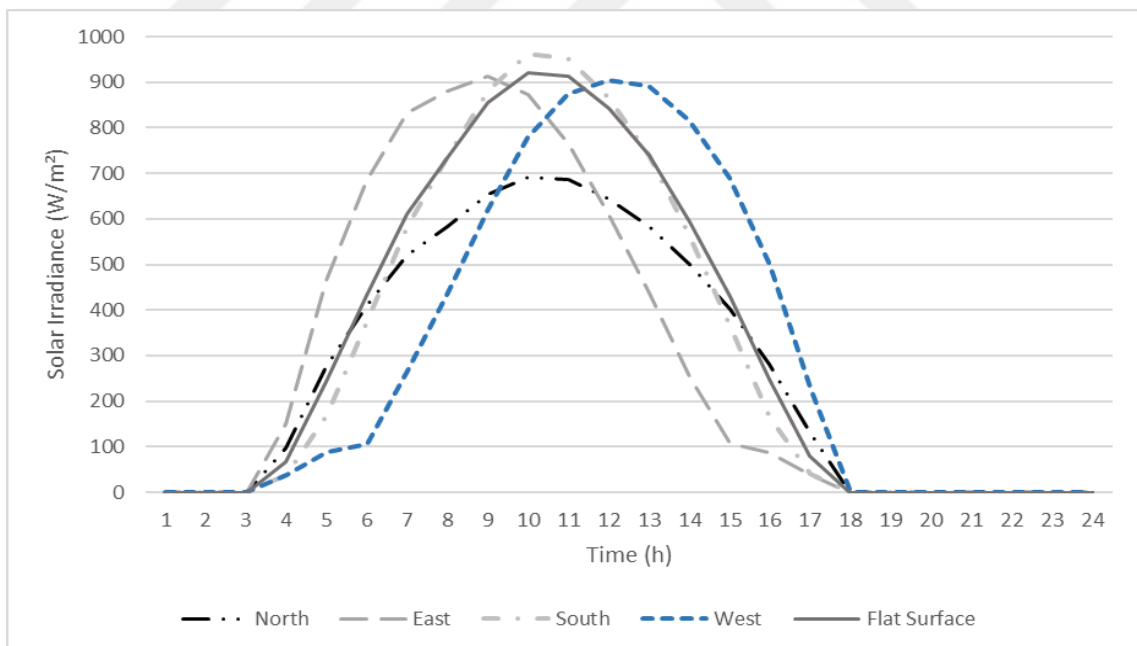


Figure A8. Monthly Averaged Daily Data of Solar Radiation in Sivas at July (Orientations Were Given for 30° Angle)

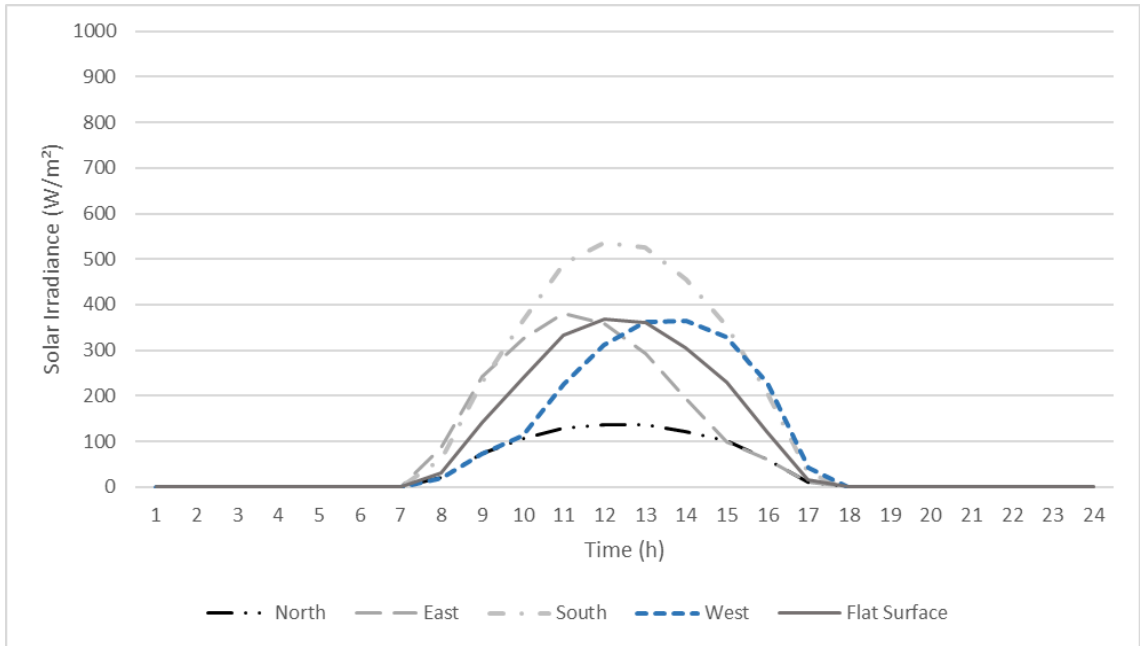


Figure A9. Monthly Averaged Daily Data of Solar Radiation in Şanlıurfa at January (Orientations Were Given for 30° Angle)

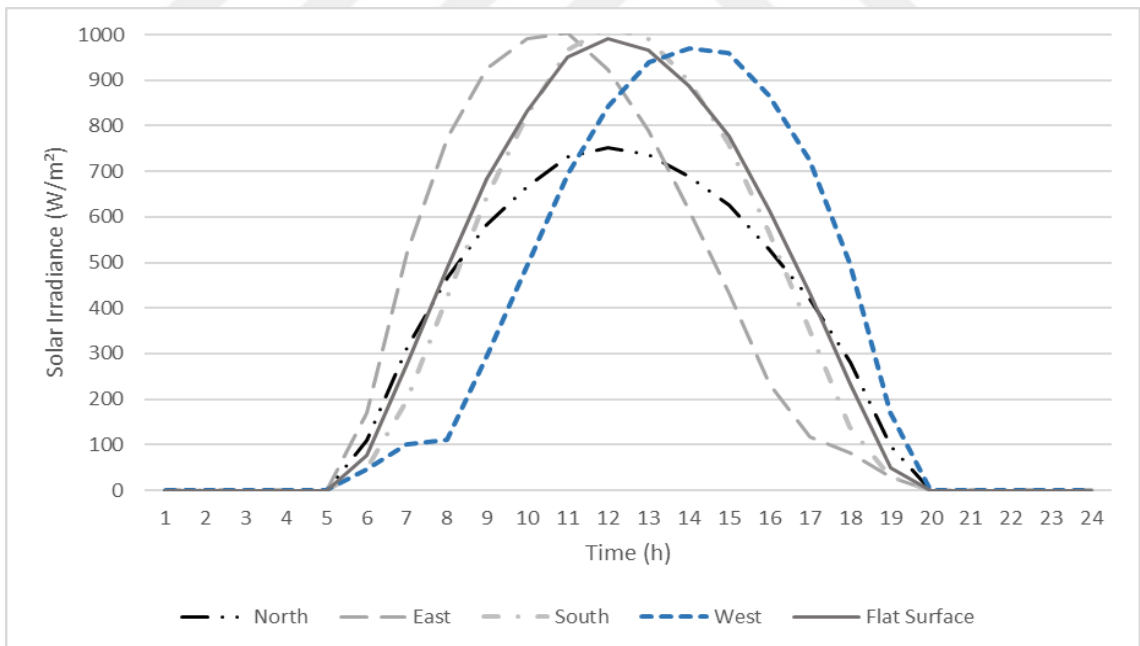


Figure A10. Monthly Averaged Daily Data of Solar Radiation in Şanlıurfa at July (Orientations Were Given for 30° Angle)

## APPENDIX B

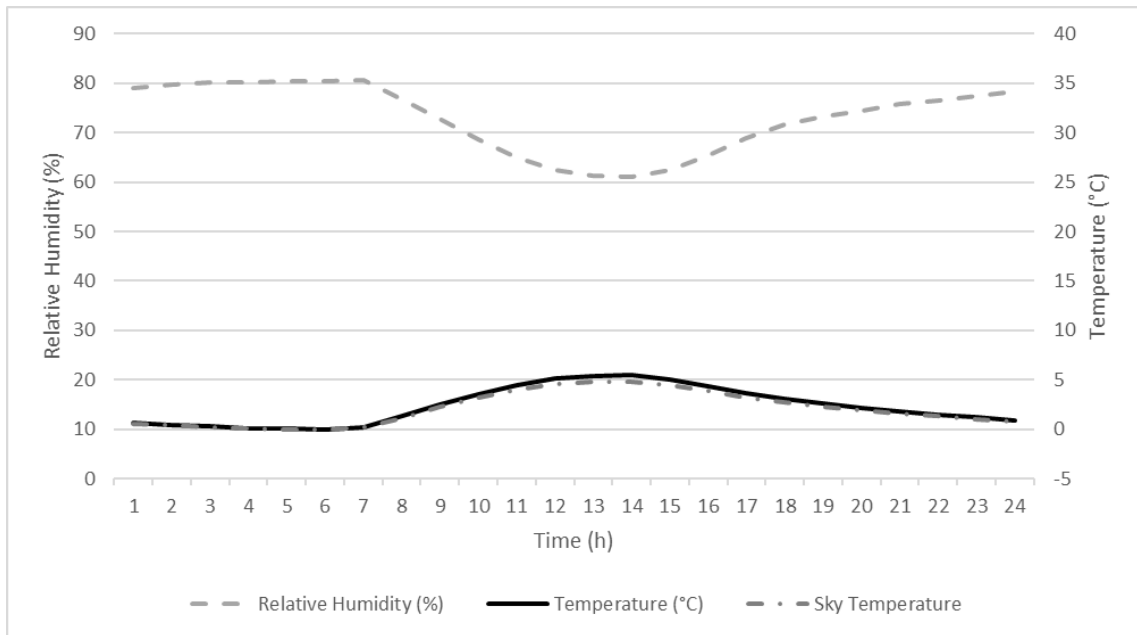


Figure B1. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Ankara at January

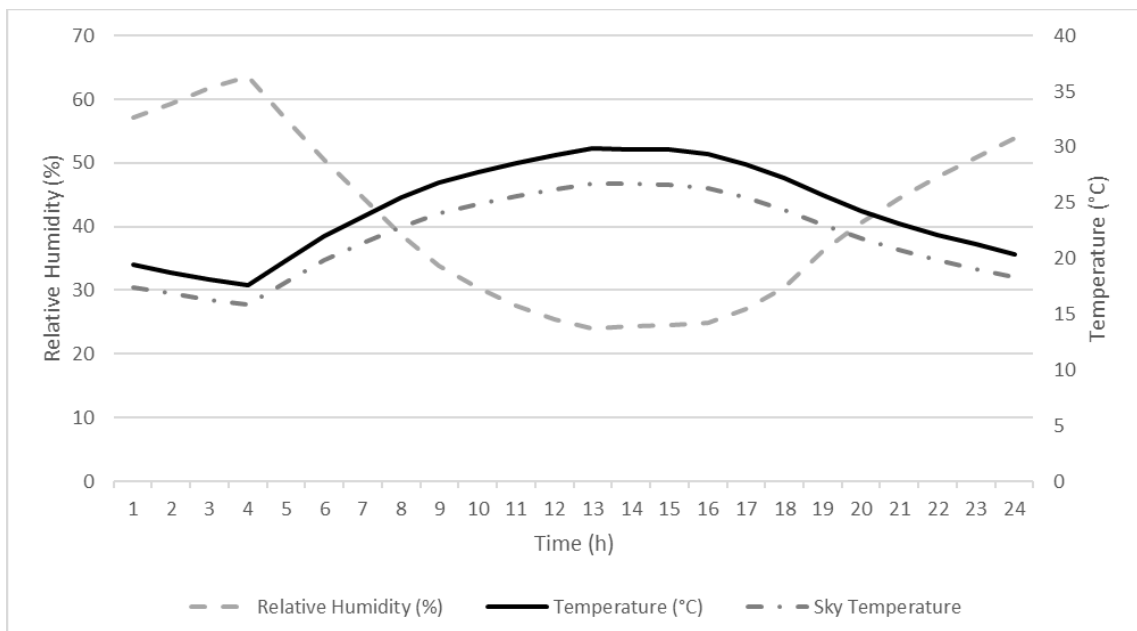


Figure B2. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Ankara at July

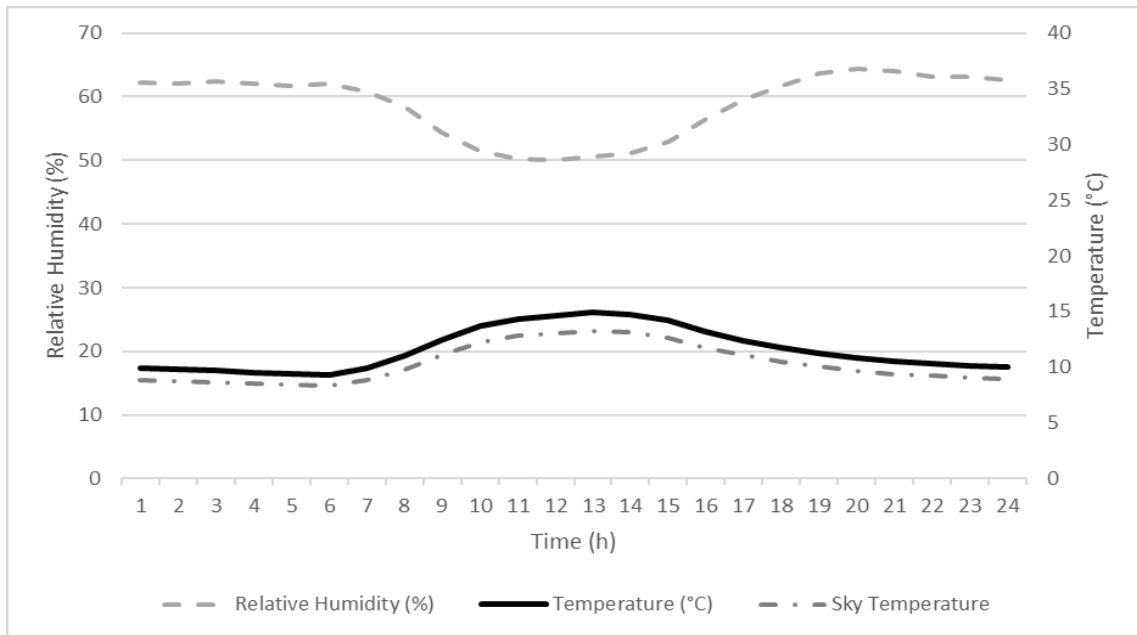


Figure B3. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Ardahan at January

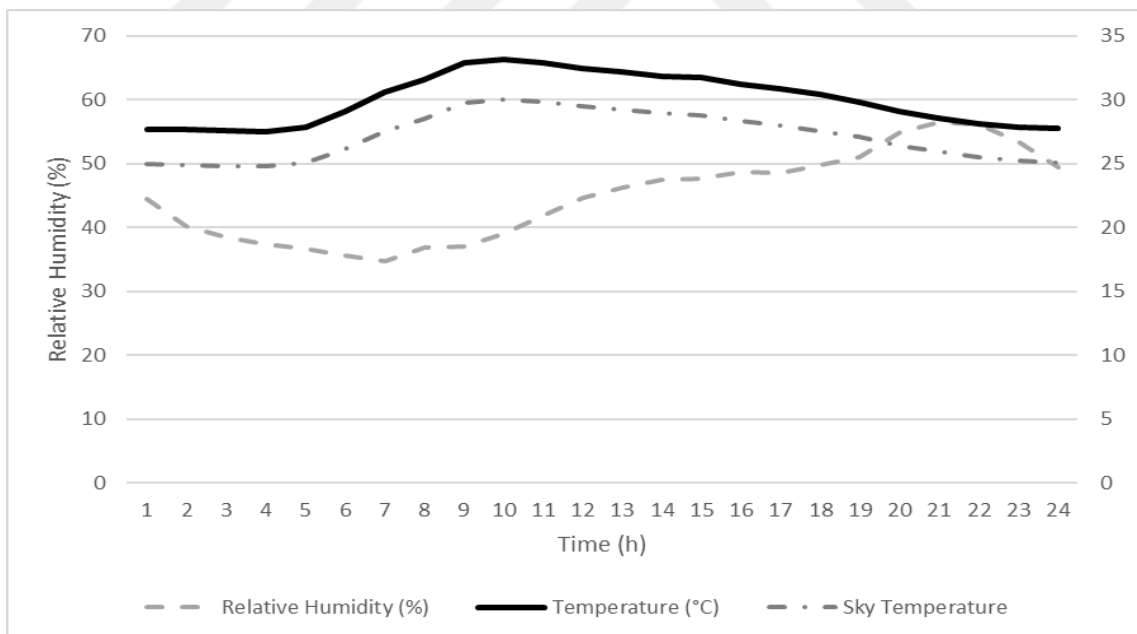


Figure B4. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Ardahan at July

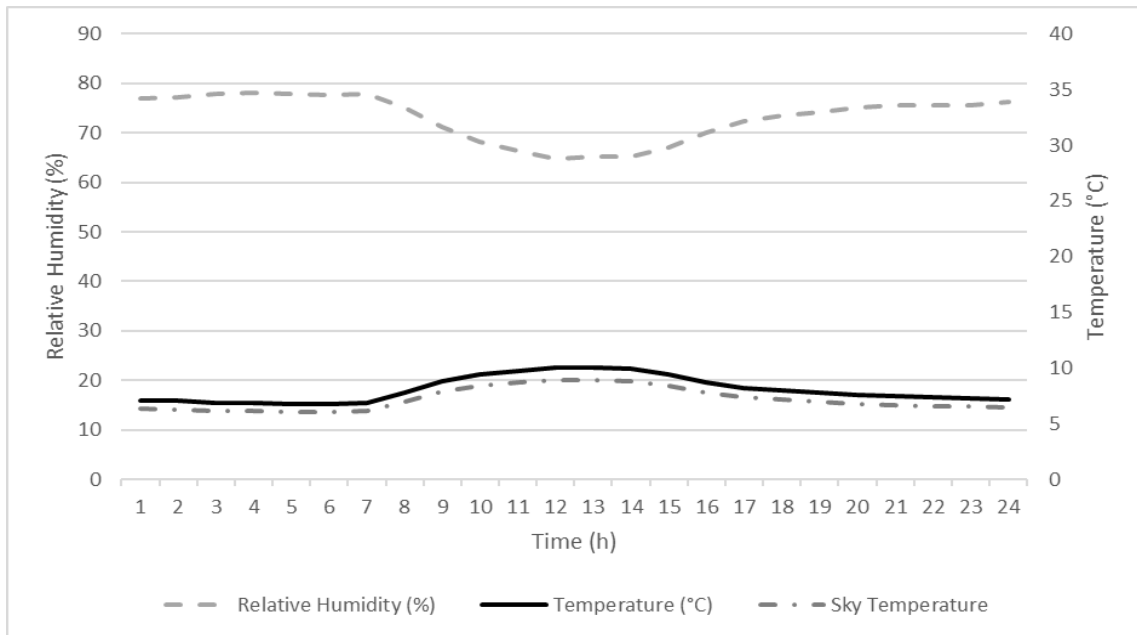


Figure B5. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in İstanbul at January

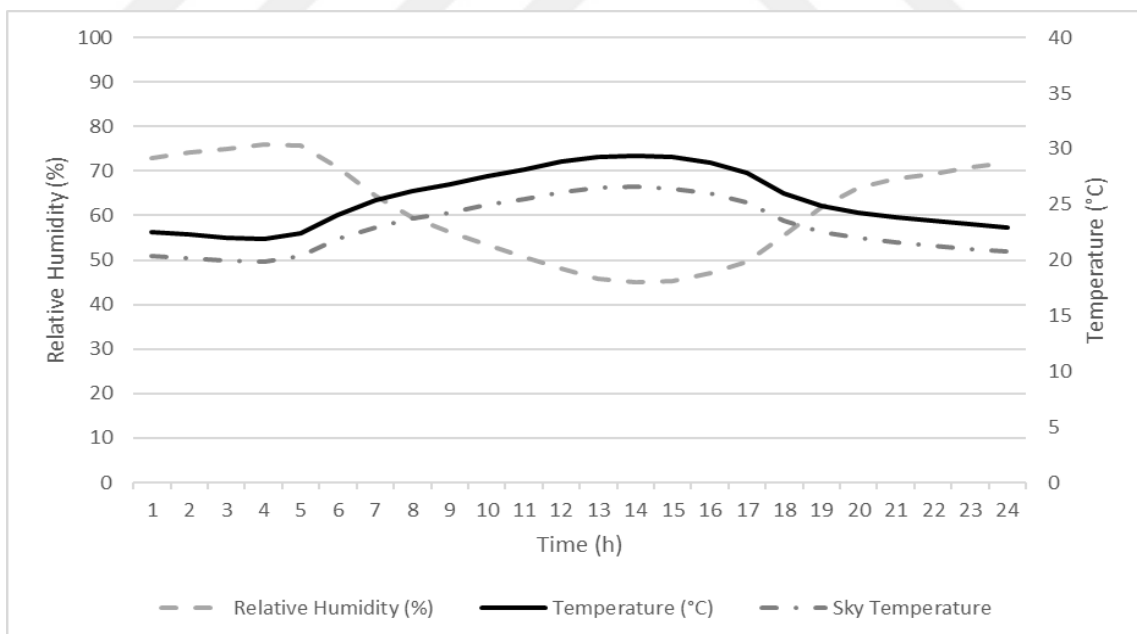


Figure B6. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in İstanbul at July

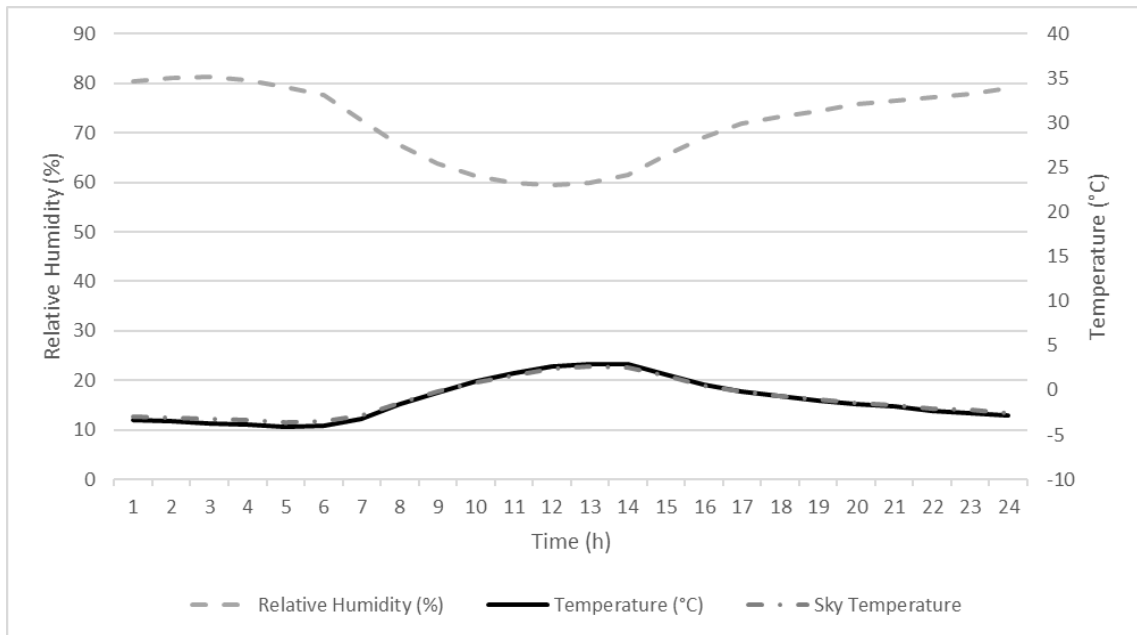


Figure B7. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Sivas at January

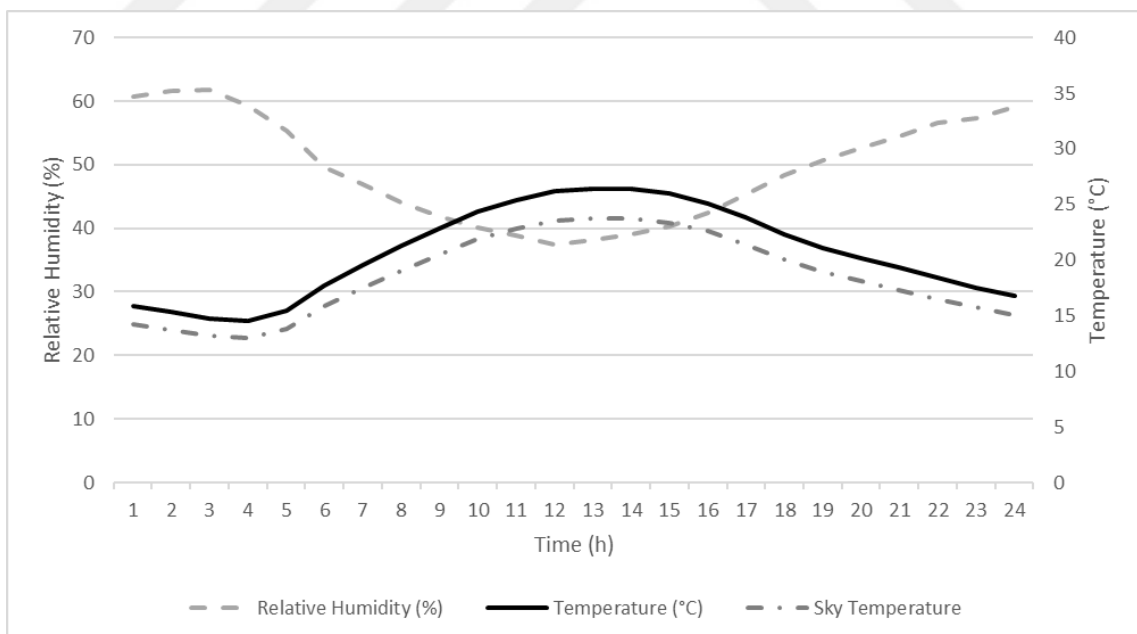


Figure B8. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Sivas at July

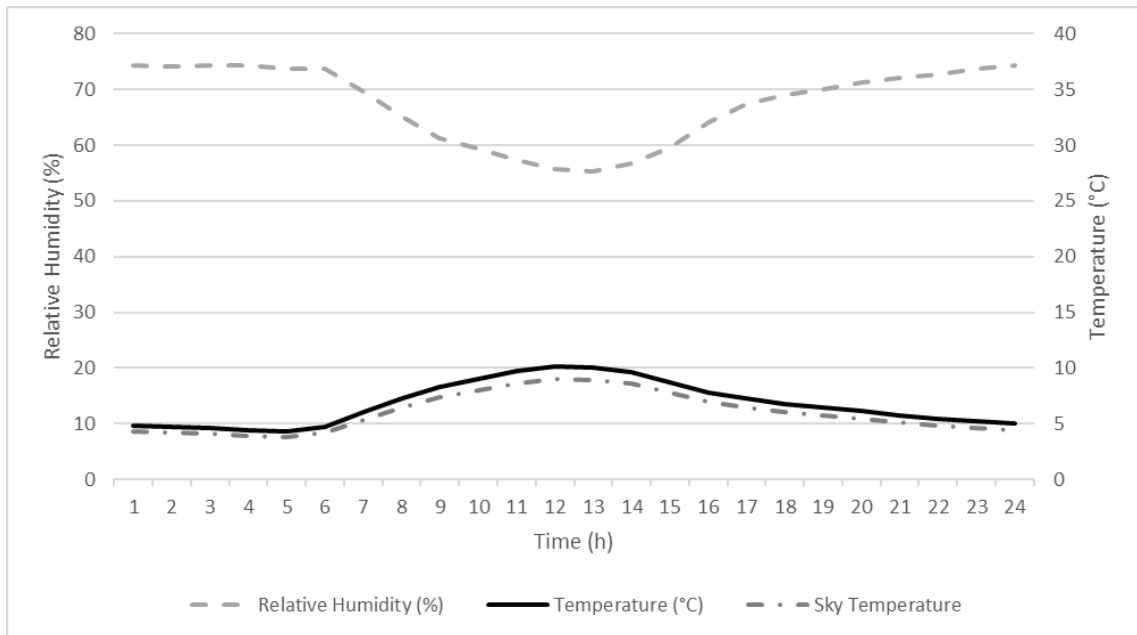


Figure B9. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Şanlıurfa at January

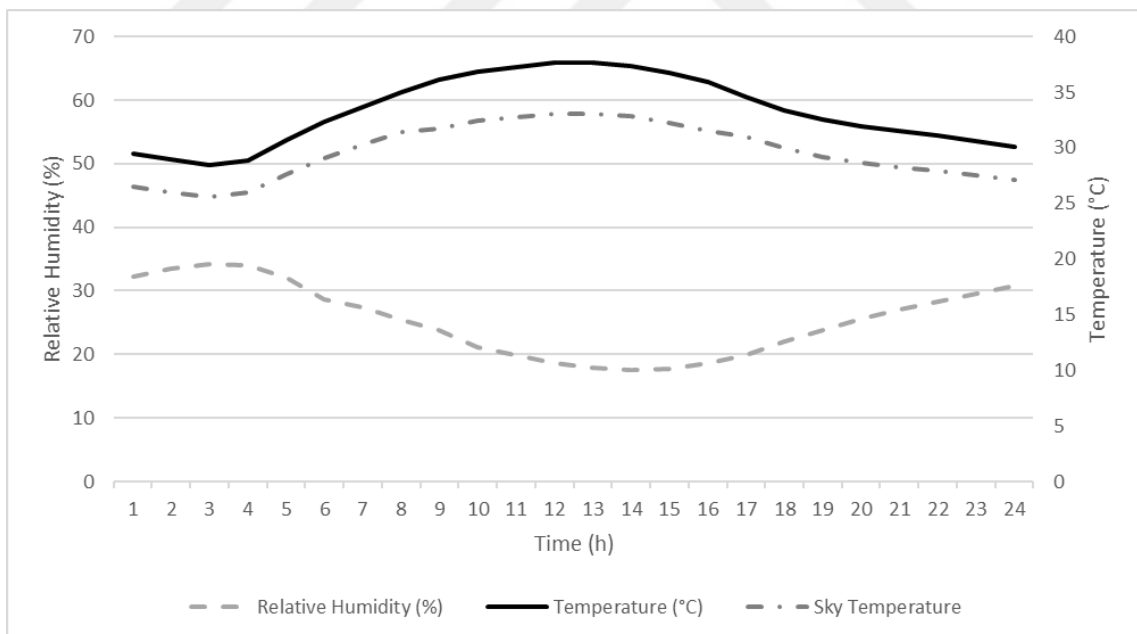


Figure B10. Monthly Averaged Daily Data of Radiative Sky Temperature Which Calculated based on Relative Humidity and Outside Temperature in Şanlıurfa at July

## APPENDIX C



Figure C1. Map of Köppen-Trewartha Climatic Zones in Turkey

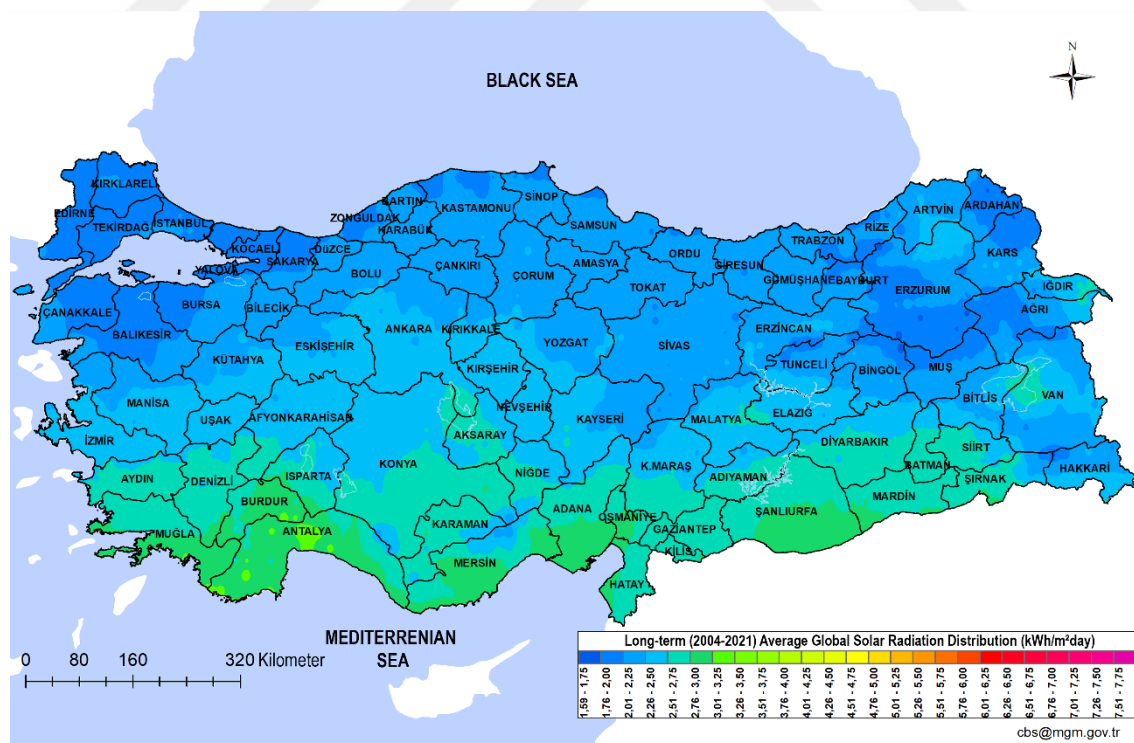


Figure C2. Map of Winter Global Solar Radiation Distribution of the Turkey, published by MGM

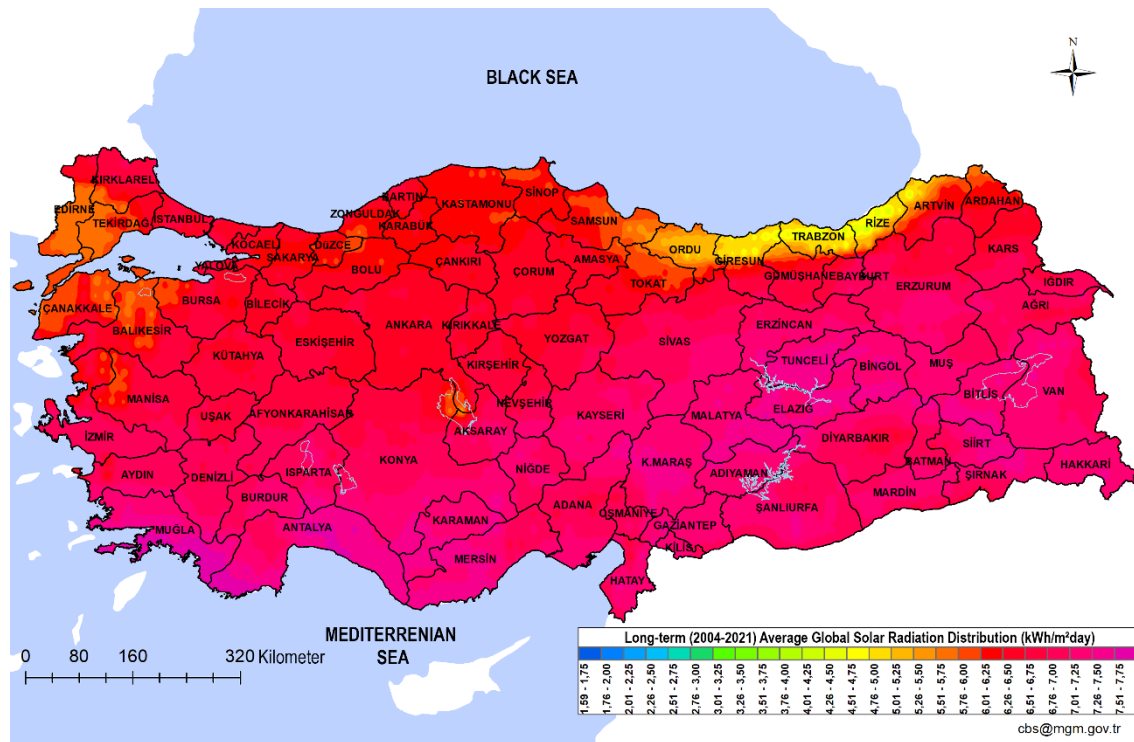


Figure C3. Map of Summer Global Solar Radiation Distribution of the Turkey, published by MGM

## APPENDIX D

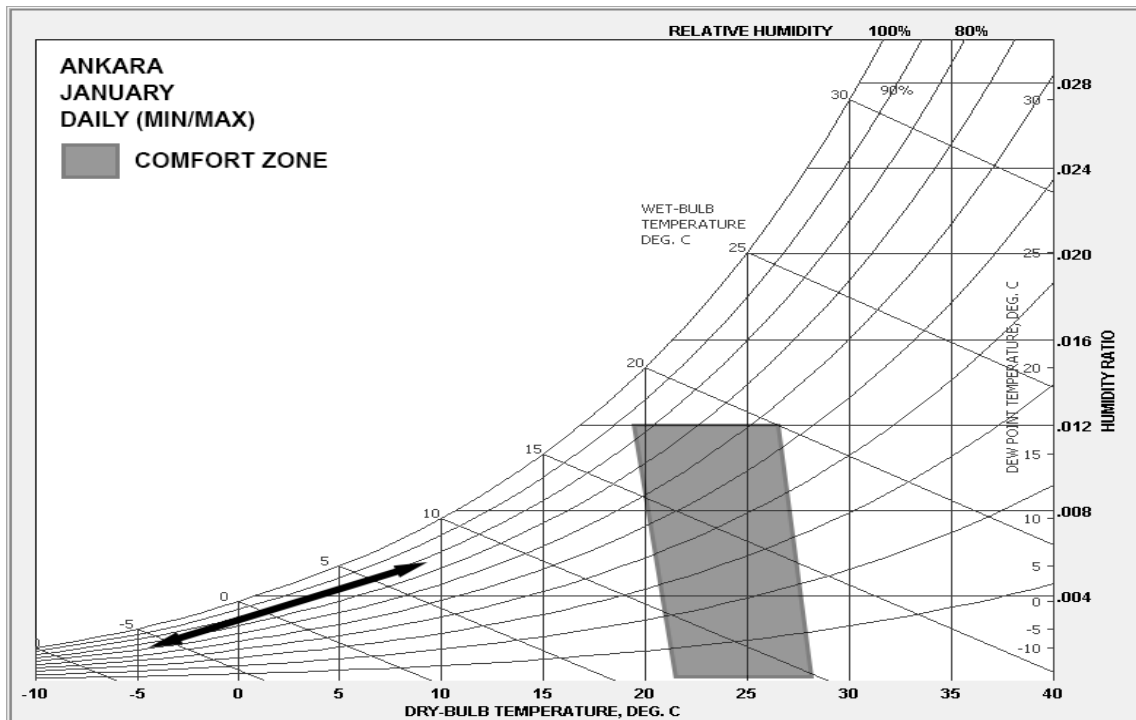


Figure D1. Psychrometric Chart of Comfort Zones January in Ankara

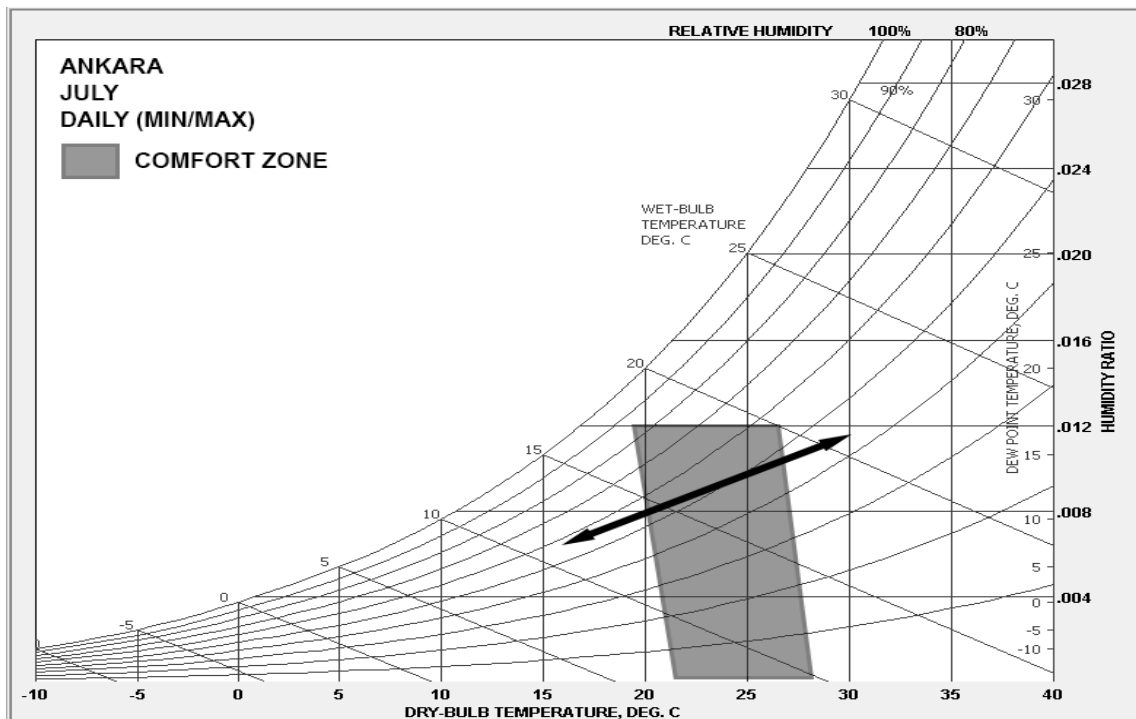


Figure D2. Psychrometric Chart of Comfort Zones July in Ankara

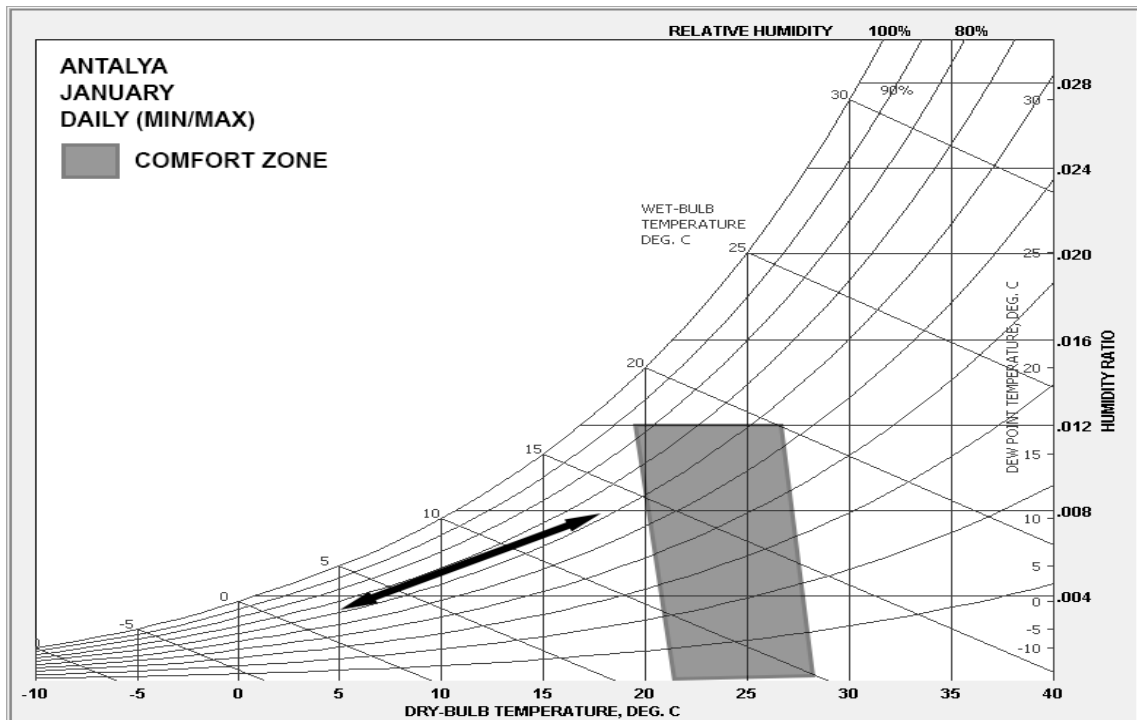


Figure D3. Psychrometric Chart of Comfort Zones January in Antalya

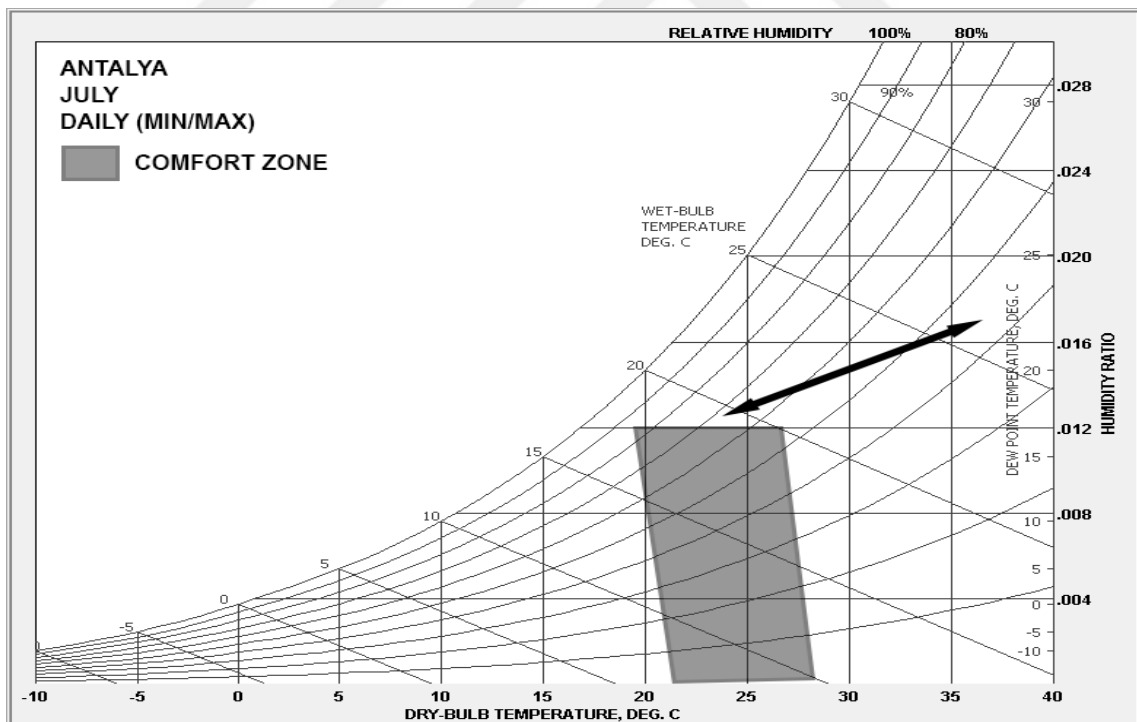


Figure D4. Psychrometric Chart of Comfort Zones July in Antalya

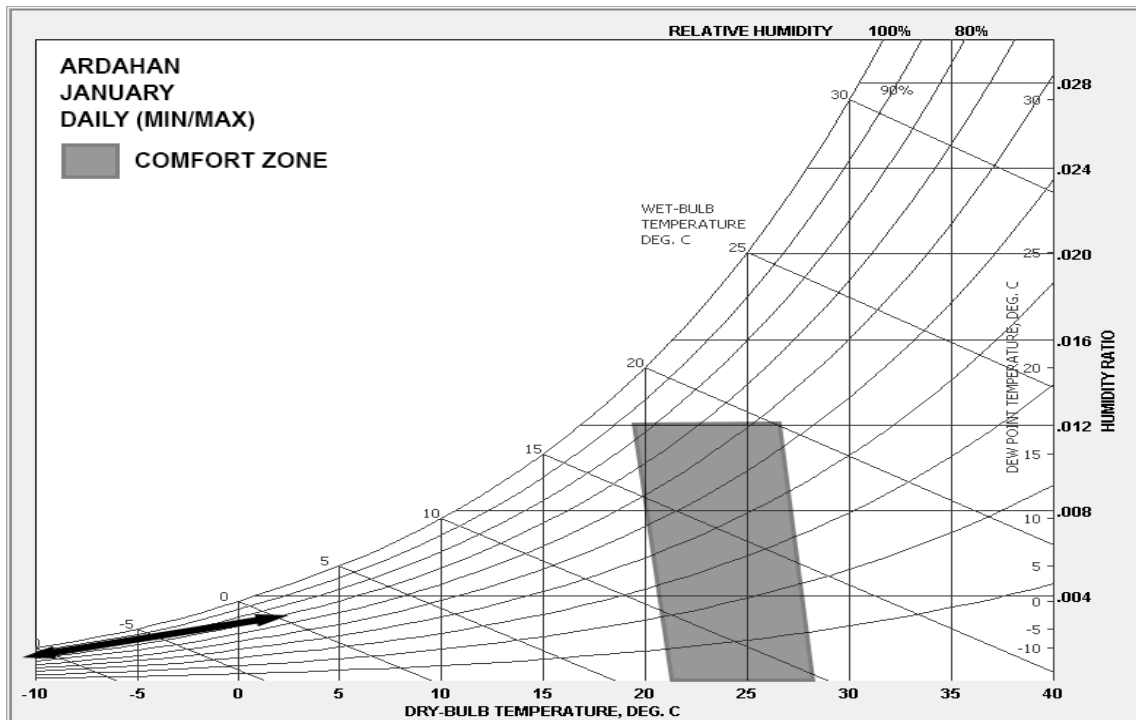


Figure D5. Psychrometric Chart of Comfort Zones January in Ardahan

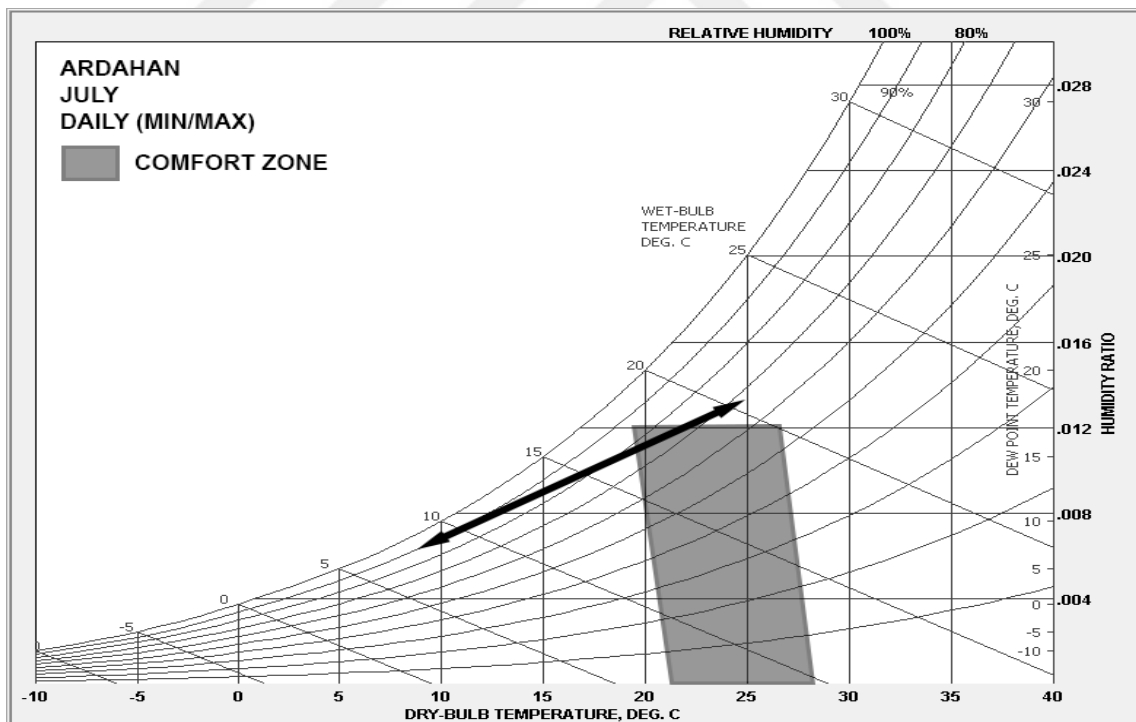


Figure D6. Psychrometric Chart of Comfort Zones July in Ardahan

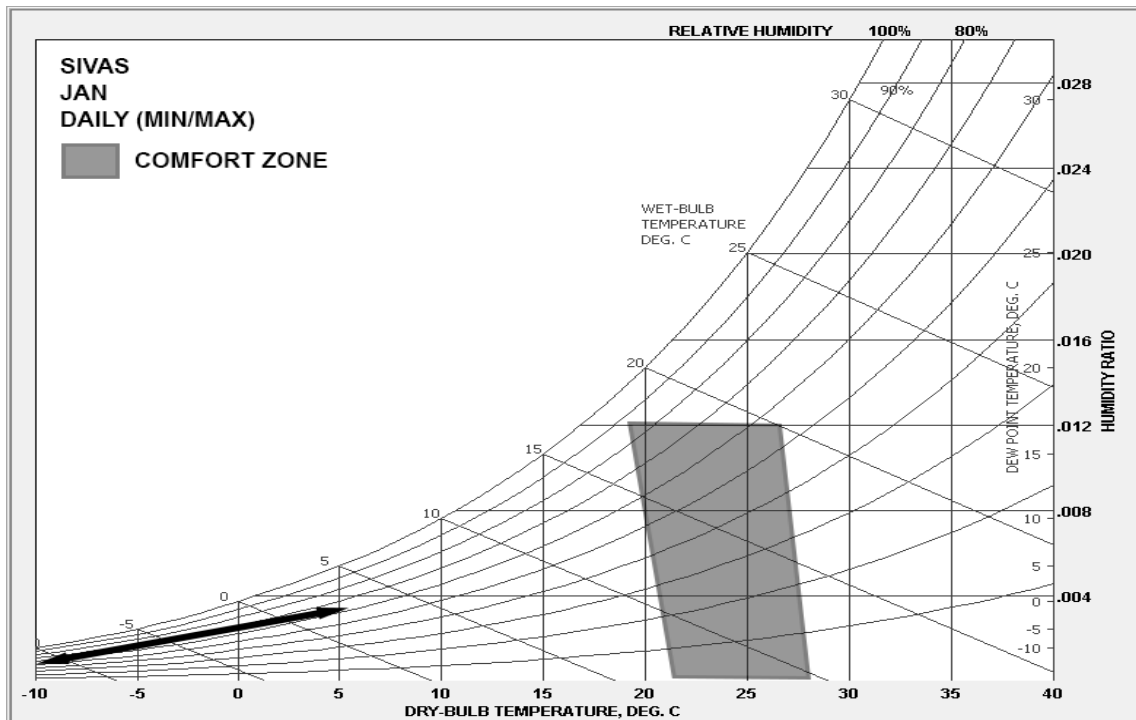


Figure D7. Psychrometric Chart of Comfort Zones January in Sivas

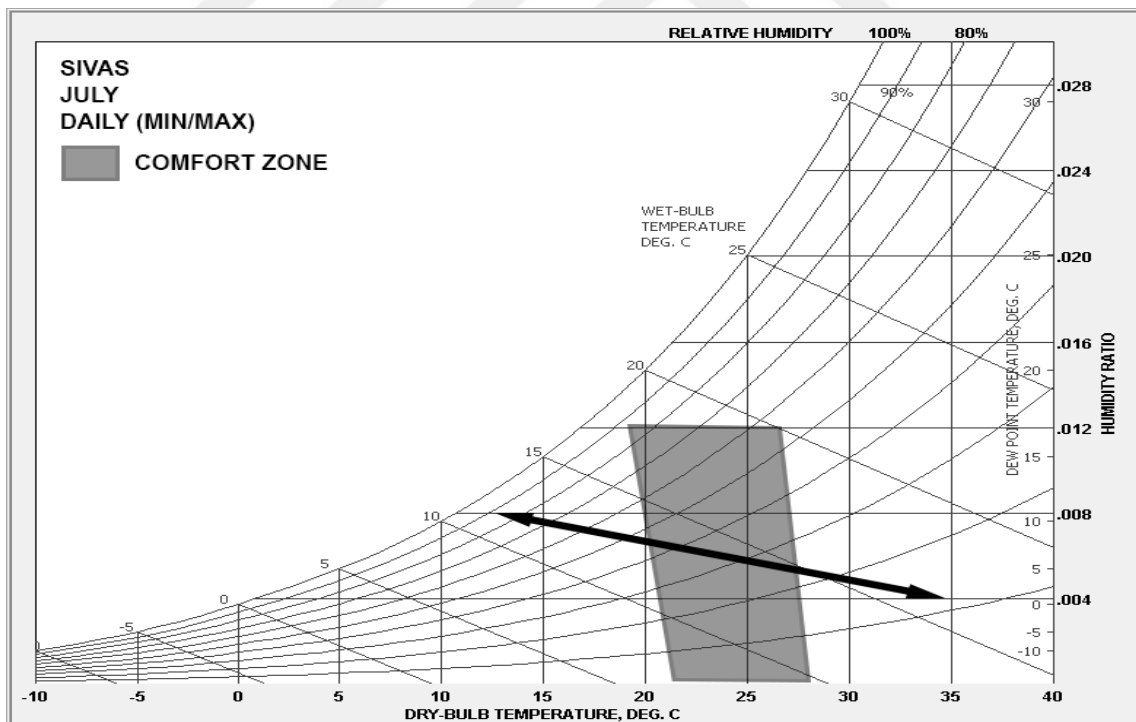


Figure D8. Psychrometric Chart of Comfort Zones July in Sivas

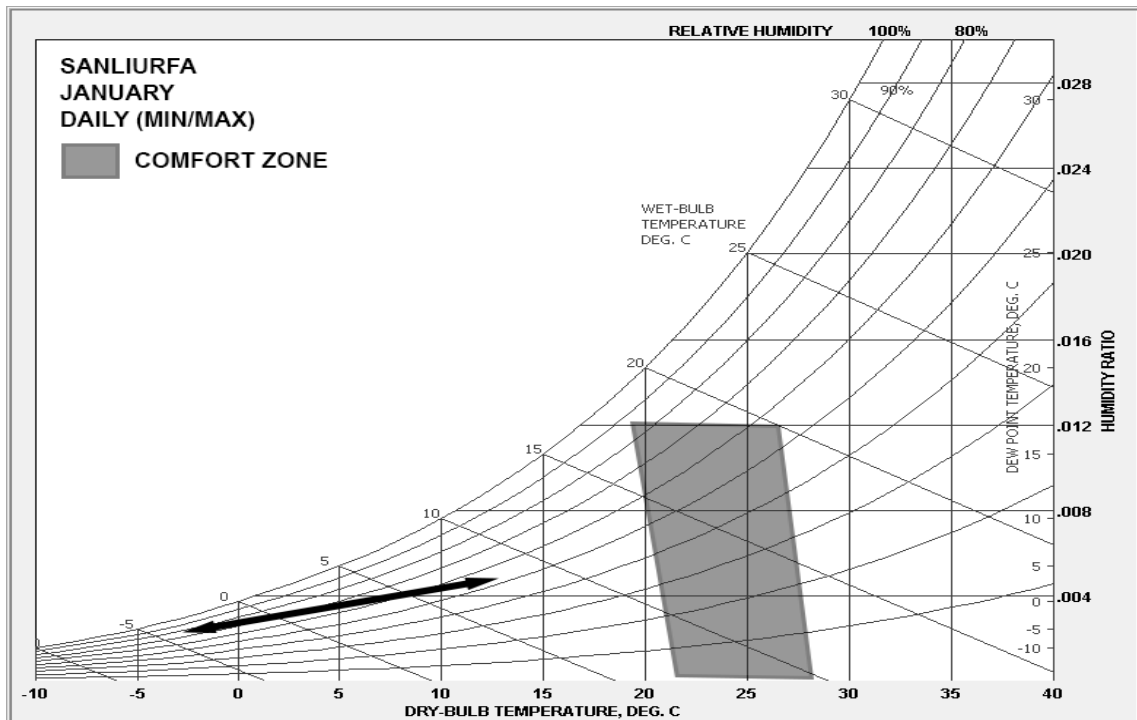


Figure D9. Psychrometric Chart of Comfort Zones January in Şanlıurfa

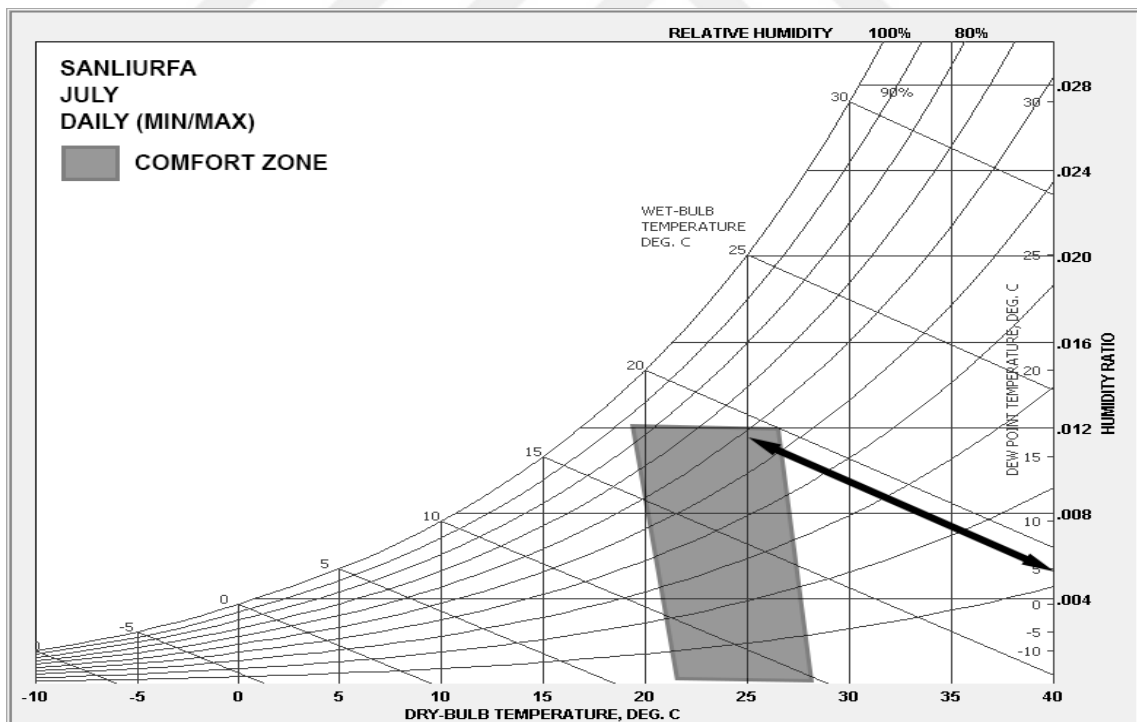


Figure D10. Psychrometric Chart of Comfort Zones July in Şanlıurfa

## APPENDIX E

| Table 4.1 Limiting U-values for new fabric elements and air permeability in new dwellings |                                                      |
|-------------------------------------------------------------------------------------------|------------------------------------------------------|
| Element type                                                                              | Maximum U-value <sup>(1)</sup> W/(m <sup>2</sup> ·K) |
| All roof types <sup>(2)</sup>                                                             | 0.16                                                 |
| Wall <sup>(2)</sup>                                                                       | 0.26                                                 |
| Floor                                                                                     | 0.18                                                 |
| Party wall                                                                                | 0.20                                                 |
| Swimming pool basin <sup>(3)</sup>                                                        | 0.25                                                 |
| Window <sup>(4)(5)</sup>                                                                  | 1.6                                                  |
| Rooflight <sup>(6)(7)</sup>                                                               | 2.2                                                  |
| Doors (including glazed doors)                                                            | 1.6                                                  |
| Air permeability                                                                          | 8.0m <sup>3</sup> /(h·m <sup>2</sup> ) @ 50Pa        |
|                                                                                           | 1.57m <sup>3</sup> /(h·m <sup>2</sup> ) @ 4Pa        |

Figure E1. Recommended U-Values of Different Building Elements for New Dwellings in the UK Building Regulations  
(Source: UK Building Regulations)

APPENDIX F

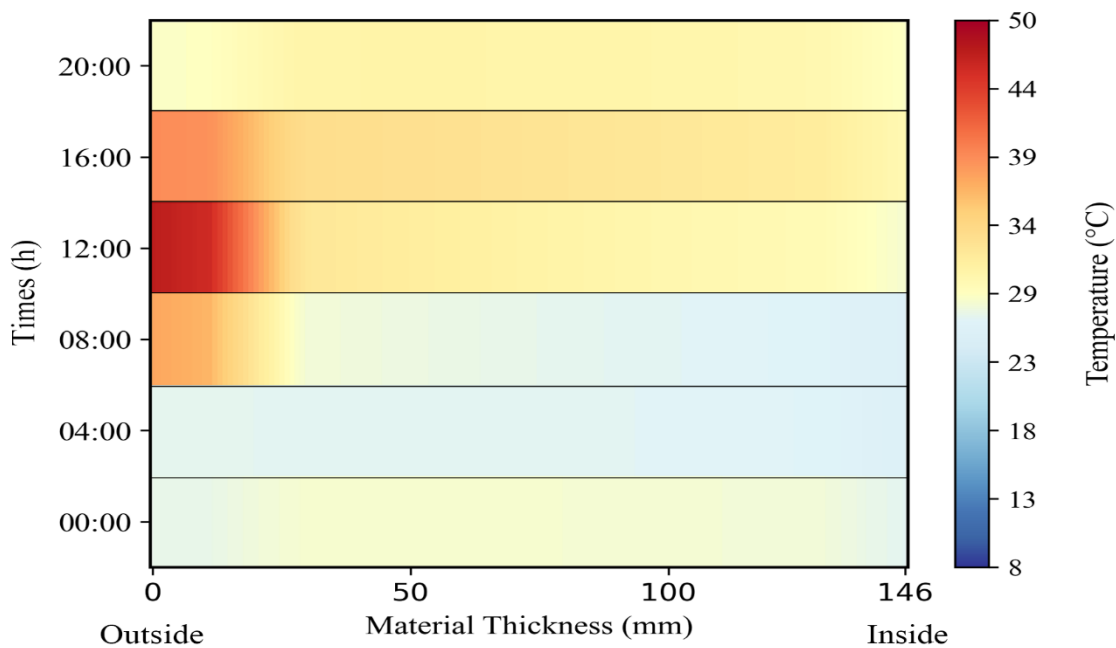


Figure F1. Temperature Distribution Through a Concrete Structure Roof in Antalya with Uninsulated Scenario in July

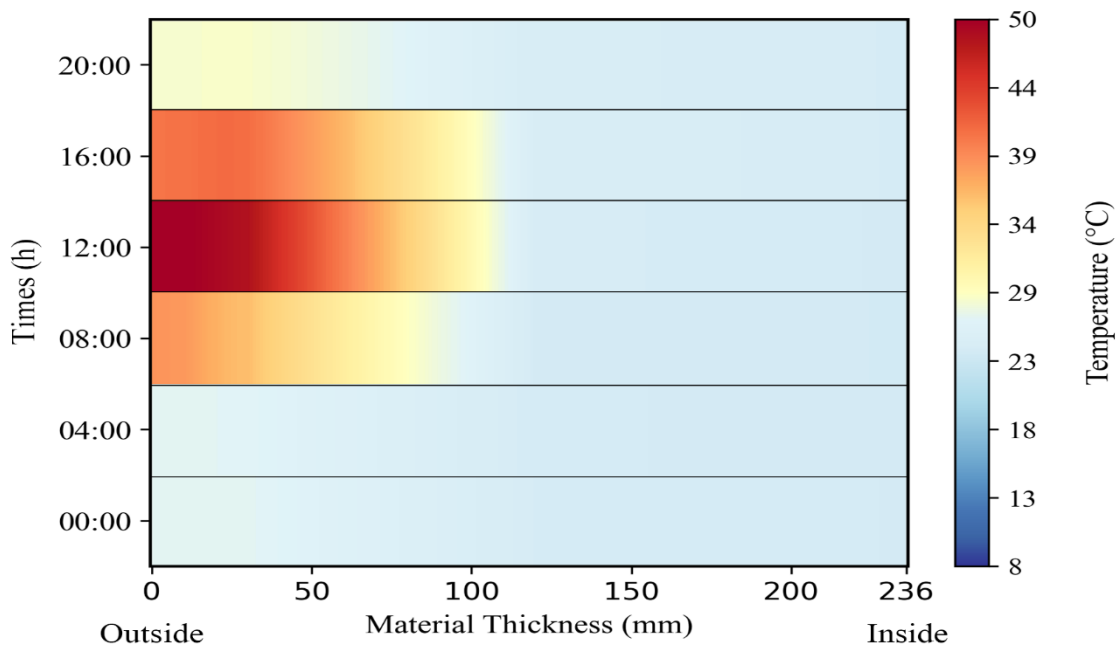


Figure F2. Temperature Distribution Through a Concrete Structure Roof in Antalya with Current TS825 Insulation Scenario in July

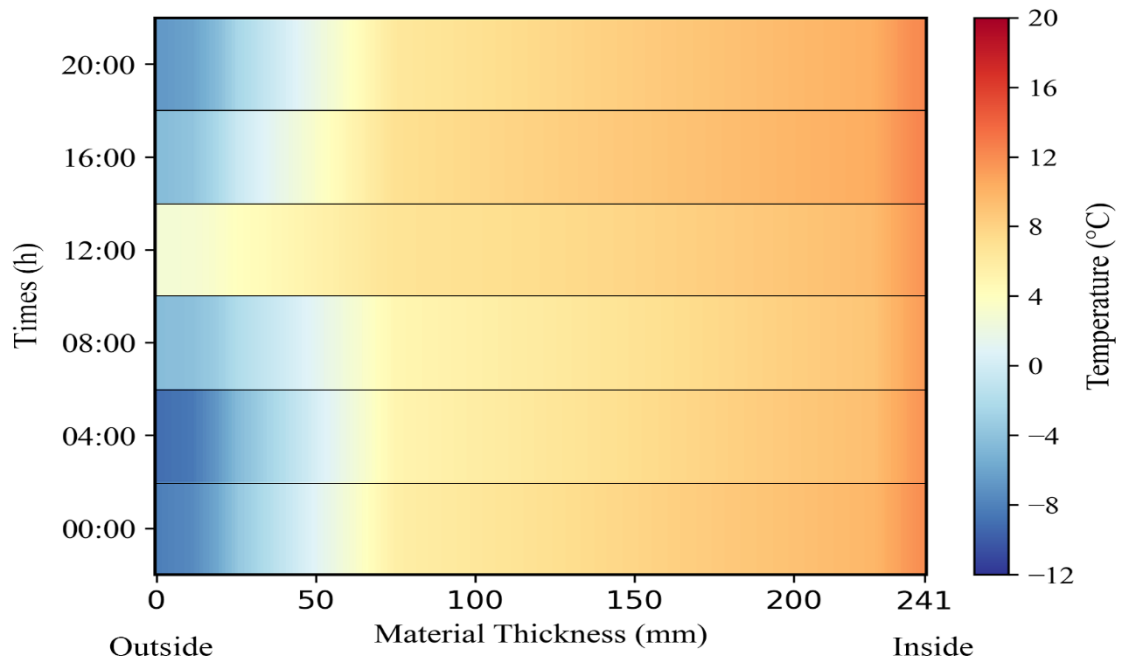


Figure F3. Temperature Distribution Through a Flat Roof in Ardahan with Uninsulated Scenario in January

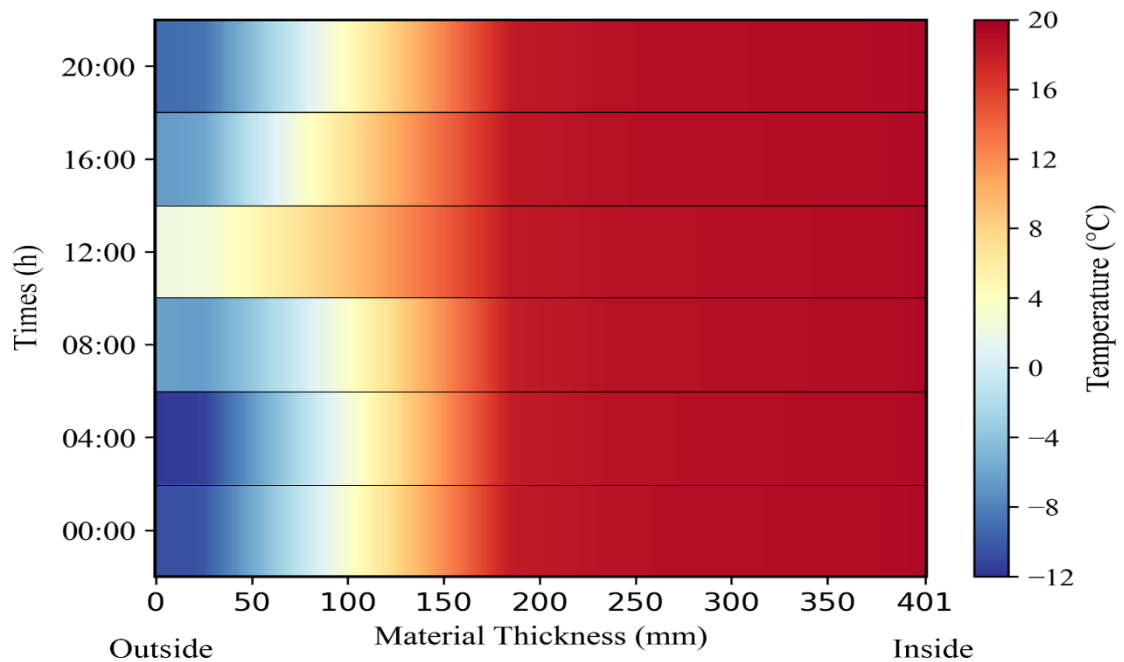


Figure F4. Temperature Distribution Through a Flat Roof in Ardahan with Current TS825 Insulation Scenario in January

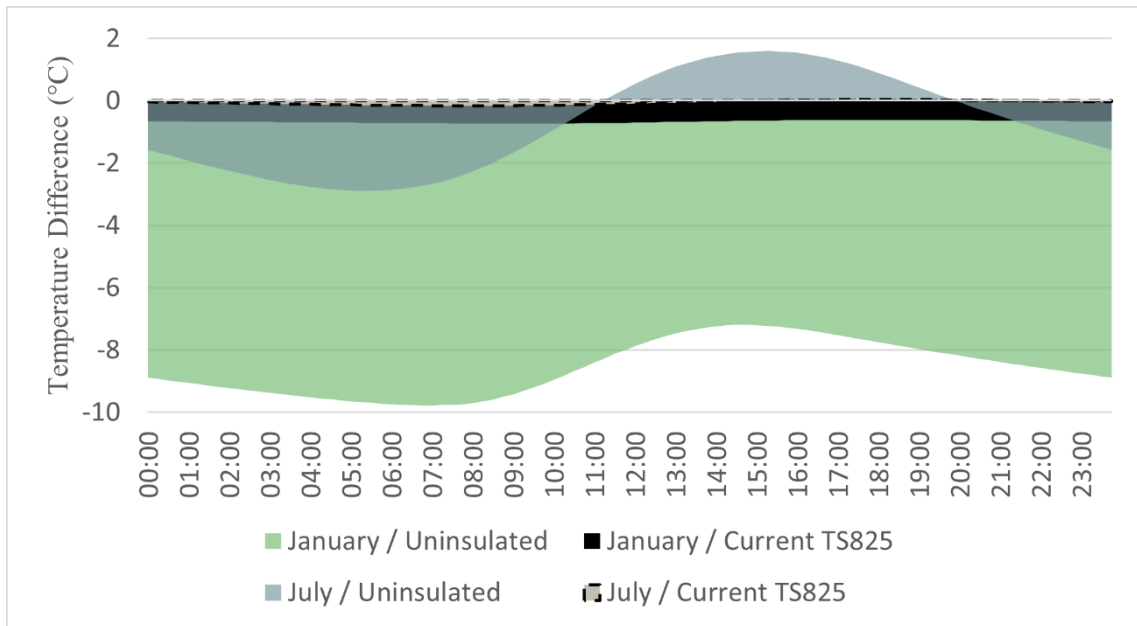


Figure F5. Diurnal variation of indoor surface temperature differences relative to indoor air temperature for insulated and uninsulated scenarios in Ardahan, for concrete structured roof (January–July comparison)

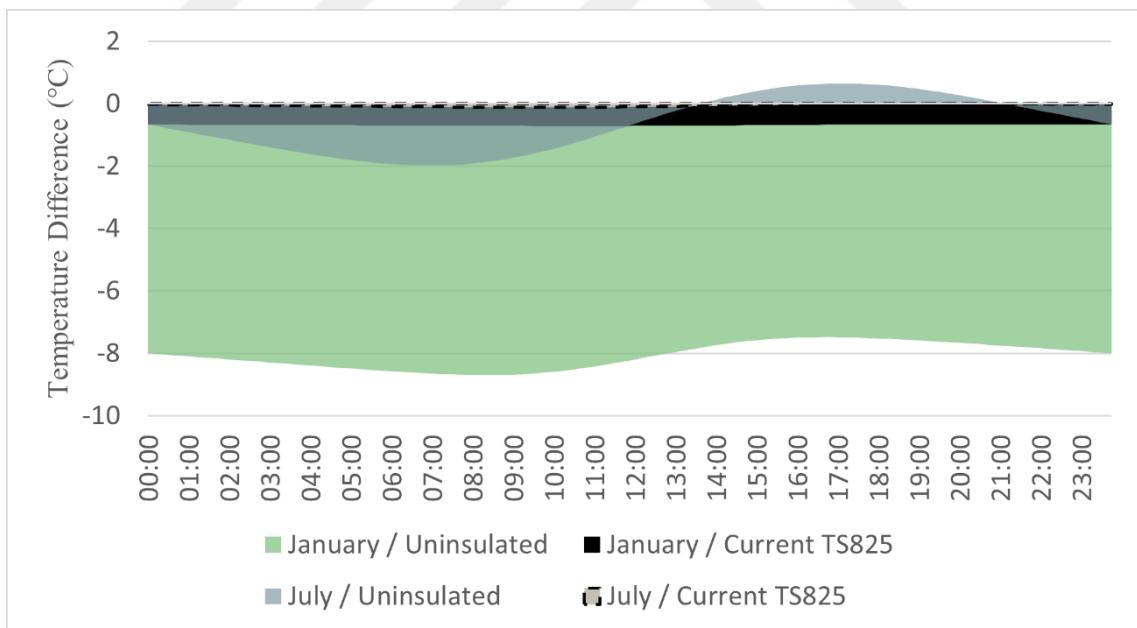


Figure F6. Diurnal variation of indoor surface temperature differences relative to indoor air temperature for insulated and uninsulated scenarios in Ardahan, for flat terrace roof (January–July comparison)