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Investigation of Thermal Comfort and Optimum Supply Water Temperature in the Double Layered Thermally Activated Building System

Oğuzhan ÇALIŞIR[1], Müjdat ÖZTÜRK[2], Gamze GENÇ[3]*

[1]*OCM Energy and Technology Co., Department of Research and Development, 38150 Kayseri, Türkiye*

[2]*Kırşehir Ahi Evran University, Faculty of Engineering and Architecture, Department of Mechanical Engineering, 40100 Kırşehir, Türkiye*

[3]*Erciyes University, Engineering Faculty, Department of Energy Systems Engineering, 38039 Kayseri, Türkiye*

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Anahtar Kelimeler

Termal Aktif Bina Sistemi (TABS)
Çift Katmanlı Termal Aktif Bina Sistemi (DLTS)
Isıl Konfor
Enerji Verimliliği
Optimizasyon

Graphical/Tabular Abstract (Grafik Özet)

The study optimizes supply water temperature in a Double Layered Thermally Activated Building System (DLTS) using GRG algorithm, ensuring thermal comfort and energy efficiency./ Bu çalışma, Çift Katmanlı Isıl Aktif Bina Sistemi'nde (DLTS) GRG algoritması ile besleme suyu sıcaklığını optimize ederek ısıl konfor ve enerji verimliliğini sağlamaktadır.

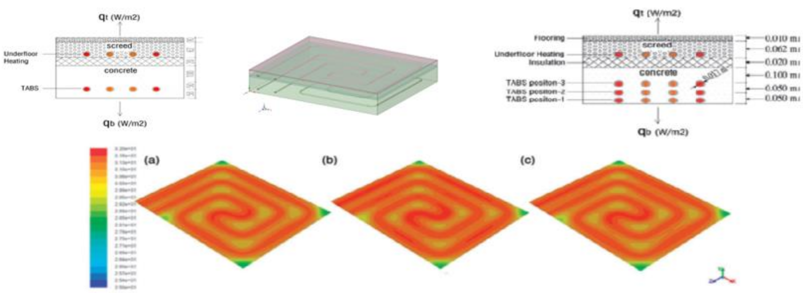

***Figure A**: DLTS system configuration and simulation results / **Şekil A:** DLTS sisteminin konfigürasyonu ve simülasyon sonuçları*

Highlights (Önemli noktalar)

- *GRG optimization identified 26.66°C as the optimum supply water temperature. / GRG optimizasyonu, optimum besleme suyu sıcaklığını 26.66°C olarak belirlemiştir.*
- *PPD values remain below 12.14% for Class C comfort, meeting ASHRAE and ISO standards. / PPD değerleri, C sınıfı konfor için %12.14'ün altında kalarak ASHRAE ve ISO standartlarını karşılamaktadır.*
- *DLTS operates with lower water temperatures than single-layer TABS, providing energy savings. / DLTS, tek katmanlı TABS'a göre daha düşük su sıcaklıklarında çalışarak enerji tasarrufu sağlamaktadır.*

Aim (Amaç): *This study aims to optimize supply water temperature in a Double Layered Thermally Activated Building System (DLTS) to ensure maximum thermal comfort with minimum energy consumption. / Bu çalışma, Çift Katmanlı Termal Aktif Bina Sistemi'nde (DLTS) besleme suyu sıcaklığını optimize ederek minimum enerji tüketimiyle maksimum ısıl konfor sağlamayı amaçlamaktadır.*

Originality (Özgünlük): *This study presents a new Double Layer TABS (DLTS) configuration, unlike traditional single-layer systems. The research improves thermal comfort and energy efficiency by optimizing pipe layout and feedwater temperature. / Bu çalışma, geleneksel tek katmanlı sistemlerden farklı olarak yeni bir Çift Katmanlı TABS (DLTS) konfigürasyonu sunmaktadır. Araştırma, boru yerleşimini ve besleme suyu sıcaklığını optimize ederek ısıl konfor ve enerji verimliliğini artırmaktadır.*

Results (Bulgular): *DLTS provides significant energy savings and improved thermal comfort compared to traditional single-layer TABS. / DLTS, geleneksel tek katmanlı TABS'a göre önemli enerji tasarrufu ve artırılmış ısıl konfor sağlamaktadır.*

Conclusion (Sonuç): *DLTS provides significant energy savings and improved thermal comfort compared to traditional single-layer TABS. It is applicable for both new buildings and retrofitting projects, contributing to sustainable building practices. / DLTS, geleneksel tek katmanlı TABS'a göre önemli enerji tasarrufu ve artırılmış ısıl konfor sağlamaktadır. Hem yeni binalarda hem de yenileme projelerinde uygulanabilir olup, sürdürülebilir bina uygulamalarına katkı sunmaktadır.*

*Corresponding author, e-mail: gamzegenc@erciyes.edu.tr
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Abstract

The adoption of low-temperature heating systems in buildings has become increasingly popular to reduce energy consumption and enhance energy efficiency. In our previous study, a novel hydronic radiant heating system integrating both Underfloor Heating and Thermally Activated Building Systems (TABS) on the same floor was developed. The optimization process was based on thermal comfort criteria defined in ASHRAE 55 and ISO 7730, using floor surface temperatures obtained via FLUENT/ANSYS simulations. The Generalized Reduced Gradient (GRG) algorithm was employed, with Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) indicators to assess thermal comfort. Present study aims to optimize the supply water temperature for the "Double Layered Thermally Activated Building System" (DLTS), ensuring thermal comfort and energy efficiency. Results indicated that for thermal neutrality, the optimum supply water temperature was 26.66°C, and the optimum surface temperature was 23.60°C. The DLTS system met the comfort criteria with PPD values below 12.14 for class C, demonstrating high user satisfaction. This research highlights the potential of DLTS to improve both energy efficiency and thermal comfort in buildings, offering valuable insights for future building system designs.

Çift Katmanlı Termal Aktif Bina Sisteminde Termal Konfor ve Optimum Besleme Suyu Sıcaklığının Araştırılması

Makale Bilgisi

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Öz

Binalarda düşük sıcaklıklı ısıtma sistemlerinin benimsenmesi, enerji tüketimini azaltmak ve enerji verimliliğini artırmak amacıyla giderek daha popüler hale gelmiştir. Önceki çalışmamızda, aynı katta hem Yerden Isıtma hem de Termal Olarak Aktive Edilmiş Bina Sistemlerini (TABS) entegre eden yenilikçi bir hidronik radyant ısıtma sistemi geliştirilmiştir. Optimizasyon süreci, ASHRAE 55 ve ISO 7730 standartlarında tanımlanan termal konfor kriterlerine dayalı ve zemin yüzey sıcaklıkları FLUENT/ANSYS simülasyonları ile elde edilmiştir. Termal konforun değerlendirilmesinde Beklenen Ortalama Karar (PMV) ve Öngörülen Memnuniyetsizlik Yüzdesi (PPD) göstergeleri kullanılmış ve Genel Azaltılmış Gradyan (GRG) algoritması uygulanmıştır. Bu çalışmanın amacı, "Çift Katmanlı Termal Aktif Bina Sistemi" (DLTS) için besleme suyu sıcaklığını, hem termal konforu hem de enerji verimliliğini sağlayacak şekilde optimize etmektir. Sonuçlar, termal denge için optimum besleme suyu sıcaklığının 26,66°C ve optimum yüzey sıcaklığının 23,60°C olduğunu göstermiştir. DLTS sistemi, sınıf C için PPD değerlerini 12,14'ün altında tutarak konfor kriterlerini karşılamış ve yüksek kullanıcı memnuniyeti sağlamıştır. Bu araştırma, DLTS'nin binalarda hem enerji verimliliğini hem de termal konforu artırma potansiyelini vurgulamakta ve gelecekteki bina sistemi tasarımları için değerli bilgiler sunmaktadır.

1. INTRODUCTION (GİRİŞ)

The primary aim of technological advancements throughout history has been to provide people with a more comfortable life. One of the most significant types of comfort that directly affects the quality of life and work efficiency is thermal comfort. Therefore, determining whether an environment

*Corresponding author, e-mail: gamzegenc@erciyes.edu.tr
DOI: 10.29109/gujsc.1739629

provides thermal comfort is of great importance. Thermal comfort or discomfort criteria are expressed by PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfaction) values. Maintaining high thermal comfort while reducing energy consumption is crucial for environmental sustainability and energy efficiency.

In this context, radiant cooling and heating systems, which offer energy savings with higher thermal comfort in comparison with conventional systems, have been developed. In particular, underfloor heating systems and thermally activated building systems (TABS), which provide low energy consumption and high thermal comfort, have become prominent in many European countries. TABS is an innovative system that provides heating and cooling through pipes embedded in the walls or floors of buildings. Additionally, low-temperature heating and cooling systems have been reported to significantly enhance building energy performance, offering substantial potential for energy savings [1-3].

Many control algorithms and strategies have been developed to enhance the energy efficiency of these systems and maintain thermal comfort. These include methods such as keeping the supply water temperature constant, adjusting it according to the outdoor temperature, and flux modulation. However, these control strategies have generally been applied to single-layer TABS systems. Radiant heating systems stand out in many European countries in terms of low energy consumption and high thermal comfort. Especially among these most widely used floor heating systems and thermally active building systems (TABS). TABS is a heating and cooling system with pipes embedded in the walls or floors of buildings.

Various studies and algorithms have been carried out for the control of heating systems to ensure lower energy consumption. These studies have been theoretically analyzed through simulations or experiments. Generally, the variables related to the control of TABS are the supply water temperature, volumetric flow rate, and operating time. Apart from these, there are also outdoor temperature, operating temperature, internal loads, and TABS surface temperature. The regulation of supply water temperature can be achieved through a number of different methodologies. The first of these is to keep the supply water temperature constant. In this control system, the TABS is mostly operated at a constant temperature (18/20/22°C) in summer months to prevent condensation, while in winter it is operated between 25°C and 30°C [4]. Olesen and Liedelt [5] stated that in buildings with low heating and low cooling loads, the temperature is set to 22°C, and the system will switch to heating when the room temperature falls below this value, and cooling when it exceeds this value. Thanks to this simple control technique, the system is continuously operated at a constant temperature without the need for complex algorithms. The second control method for supply water is to write the supply water temperature as a function of the outdoor temperature. According to the studies carried out by Olesen and Dossi [6,7], if the supply water temperature is given separately in summer and winter as a function of the outdoor temperature, the supply water temperature is calculated as 22˚C in summer and 25˚C in winter. Controlling the supply water temperature according to the outside temperature provides low energy consumption and acceptable indoor weather conditions. Another control method is flux modulation control. Flux modulation control is to heat or cool per unit area in proportion to the temperature difference between the room air and the floor surface temperatures [8-10]. It has been observed that flux modulation control responds more quickly to sudden changes in internal loads than temperature modulation.

Simmonds [11] suggested controlling the supply water temperature based on the surface temperature of the ground. For underfloor cooling, controlling the floor temperature with a constant supply water temperature of 19-20 ºC was suggested. However, they did not evaluate thermal comfort and energy use. Baumgartner and Brühwiler [12] developed a 3-pipe system (2 outlets and 1 return) via variable supply water temperature for rooms with different heating/cooling loads. In this system, for example, in summer, frequently used rooms with medium cooling loads can operate with lower supply water temperature than empty rooms. The temperature difference between the supply water pipes is adjusted to 1-2 degrees. There is a valve to switch between pipes. This system configuration takes into account the different usage and comfort conditions of offices but requires higher installation costs and more complex control and operating algorithms. Nüβle [13] proposed a low-energy non-residential building using both the central and near-surface TABS system. This TABS configuration works with 3 pipes. One pipe feeds the pipes in the center, while the other feeds the pipes near the surface. This system also requires complex control and operating algorithms. Another form of control is the average water temperature control. The effect of controlling average water temperature (difference between flow and return) was found to be lower in terms of comfort and auxiliary energy use compared to supply water temperature control [14].

Another approach to controlling the TABS is to adjust the volume flow rate as a function of room temperature. This control system has on-off controls. It is one of the most straightforward and commonly used control strategies of TABS. Zaheer-uddin et al. [15] proposed a multi-step on-off control. Here, a 3-way valve adjusts the supply water temperature of the system. The volumetric flow rate is adjusted to 100%, 50%, or 0% based on the room temperature. The bypass is used to increase the supply water temperature in summer and decrease it in winter. The overall volume flow rate stays constant. This can offer an economic advantage for TABS, but it does not reduce the power consumption or the operating time of the pumps. TABS's working time is another control method. Continuous operation of the TABS in heating or cooling mode increases the additional energy usage, although it gives better results in thermal comfort compared to on-off control. According to the study of Athienitis and Charron [16], in the temperature difference between the setpoint and the actual room temperature, the heating energy proportional control has increased the working time compared to the traditional on-off control. On-off control leads to the system being activated frequently and the room temperature fluctuating. Tötdli et al. [17] proposed an integral approach for controlling TABS. A dynamic thermal chamber model was used to assess the impact of internal loads and solar gains on the heating and cooling load. The control input parameters include outdoor air temperature, supply water temperature, and room temperature. The main control algorithm is to determine the supply water temperature as a function of the 24-hour average outdoor temperature and room temperature. Based on the heating and cooling curves, the supply water temperature is adjusted to meet the load demand. Gwerder et al. [18] proposed the pulse width modulation (PWM) approach to control TABS. In this intermittent model of operation, PWM operates the zone pump intermittently to provide the most efficient control. In the study, two separate PWM solutions were compared and it was concluded that both were sufficient for TABS control. Sourbron and Helsen [19] investigated a model-based predictive controller (MPC) to control TABS and Air Handling Unit (AHU) using MATLAB and TRNSYS to provide thermal comfort with minimum energy consumption. The results revealed that MPC improved energy consumption and thermal comfort compared to traditional control methods. Schmelas et al. [20] proposed a self-learning predictive method based on multiple linear regression (MLR) using MATLAB and TRNSYS for TABS control. The proposed method was compared with traditional control methods. The results showed that thermal comfort was improved according to PMV-PPD requirements and there was no need for parameterization of cooling-heating curves. Qu et al. [21] investigated three different methods for the control of TABS in Beijing. As the basic control method, they examined the supply water temperature depending on the outside air temperature. Another control method is the pre-cooling control during the weekend night hours. The third control method is the optimum control of the supply water temperature. The three control methods were compared in terms of thermal comfort (according to PMV-PPD requirements) and energy consumption. As a result, it was understood that the discomfort of the basic control was high. For this reason, the other two control methods were used together to optimize the supply water temperature. In this way, thermal comfort was improved and energy consumption was reduced by 35%. Michalak [22] conducted measurements for 4 months in an office building in Poland equipped with a thermal active building system to determine PMV, PPD, surface temperature, and vertical temperature distribution. The analysis showed that the TABS system provides good thermal comfort. The measurements revealed that the average surface temperature ranged from 20.6°C to 26.2°C, the average vertical air temperature ranged from 22.5°C to 23.1°C, and the PMV value ranged from 0.52 to 1.50. Stoffel et al. [23] conducted a detailed comparison of the most commonly used advanced building control methods in a single-zone office model (based on ASHRAE 140 and 900) where heating and cooling needs are met by an air handling unit and a thermal active building system. They compared a traditional reinforcement learning-based controller method with advanced model predictive control (MPC) methods (white-box, adaptive gray-box, adaptive black-box andapproximate white-box). They evaluated the results based on annual energy consumption and discomfort. The traditional method is faster in terms of calculation time, but performs worse. The adaptive black-box MPC has demonstrated the best performance among the advanced methods. It shown a performance that is 4.9-8.4% better than others in terms of energy saving, and 7.8-83.8% better in terms of discomfort. Liu et al. [24] simulated a residential building with low energy consumption using a heat pump and TABS, using a software program. They developed an EMPC (Economic Model Predictive Control) method to reduce costs and energy consumption and compared it to the RBC (Rule-based control) method. The analysis showed that EMPC has lower energy costs compared to RBC. It was also observed that EMPC control can provide optimal heating without compromising thermal comfort and significantly reduces energy consumption at peak load.

All the control methods mentioned to increase thermal comfort are suggested for standard single-layer TABS systems. In standard TABS systems, the control of the supply water temperature is seen to be the simplest and most effective method. Even precise control methods such as MPC proceed by taking this control as the ultimate control parameter for their method.

The novelty of this study is to optimise the thermal analysis results of a double-layer TABS system (DLTS) in terms of thermal comfort, a topic that is not covered in the existing literature. In this context, optimizing the supply water temperatures based on surface temperature has allowed the determination of the limit values for comfort classes A, B, and C according to ASHRAE and ISO 7730 standards. This study highlights the advantages of DLTS systems in terms of energy efficiency and thermal comfort, providing valuable insights for future building system designs.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Terminology and Comfort Conditions (Terminoloji ve Konfor Koşulları)

According to ASHRAE and ISO 7730 standards, the general thermal comfort model has two main indicators. These are the predicted percentage of dissatisfied (PPD) and predicted percentage of mean vote (PMV) indicators. PPD is the percentage of discontent in the indoor environment, and PMV is the average comfort value in the environment. PMV is a measure of how people perceive the environment thermally, and on the scale, +3 indicates that it is very hot, 0 is neutral and -3 indicates that it is very cold. PPD value is the measure of how dissatisfied people are with the environment as a percentage of people sharing an environment using the PMV value. The PMV value varies between -3 and +3 values, while the PPD indicator varies between 0-100 values.

The relationship between PMV and PPD is shown in Figure 1. When this figure is examined, the situation where the PMV value approaches zero and the PPD value is at 5% indicates the most ideal ambient condition.

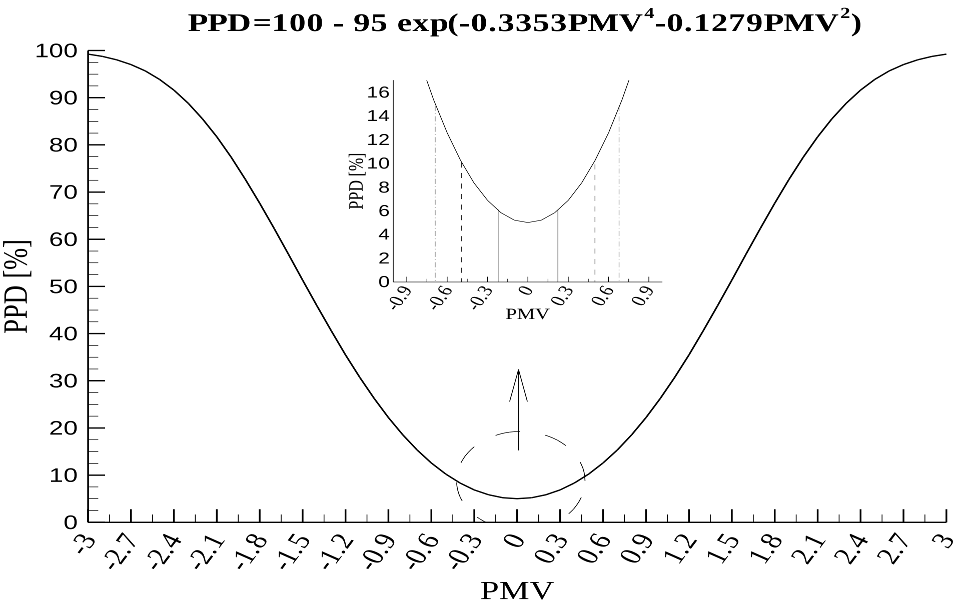


Figure 1. Relationship between PPD and PMV (PPD ve PMV arasındaki ilişki)

The general thermal comfort model, as per the ISO 7730 and ASHRAE 55 standards, includes three comfort classes: A, B, and C. According to these comfort classes, A class is limited to <6 PPD, B class <10 PPD, and C class <15 PPD. Value ranges of PPD and PMV indicators according to comfort classes are shown in Table-1.

Table 1. Thermal comfort classes based on ISO 7730 and ASHRAE 55 standards [25,26] (ISO 7730 ve ASHRAE 55 standartlarına dayalı termal konfor sınıfları)

Comfort Class	PPD Indicator (Percentage of Dissatisfaction)%	PMV Indicator (Comfort = thermal sensitivity)
A	< 6	-0.2 < PMV < 0.2
B	< 10	-0.5 < PMV < 0.5
C	< 15	-0.7 < PMV < 0.7

3. DOUBLE LAYERED THERMALLY ACTIVATED BUILDING SYSTEMS (DLTS)
(ÇİFT KATMANLI TERMAL AKTİF BİNA SİSTEMLERİ (DLTS))

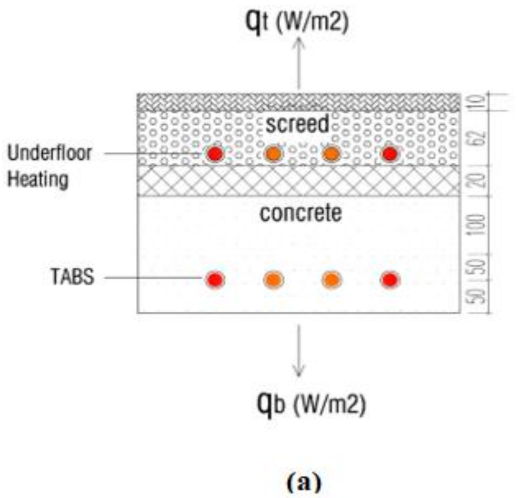
3.1. Modeling and numerical results of DLTS
(DLTS'nin Modellenmesi ve Sayısal Sonuçları)

A new design has been developed for hydronic radiant heating systems [27]. This newly developed design is a double-layer thermal active building system (DLTS), shown in Figure 2, created by combining underfloor heating and TABS system. Three-dimensional thermal analyzes of this system according to different positions of the pipes and supply water temperatures were made numerically with the FLUENT/ANSYS program [28]. As the pipe material, Pe-Xa pipe, which is 17x2.0 mm in size and which is mostly used in underfloor heating, was chosen. It has been assumed that the pipes were laid in snail type with 0.15 m between them.

Numerical analysis was conducted in steady-state conditions by means of the SIMPLE algorithm and standard k-Ɛ turbulence model. Boundary conditions included fixed ambient temperatures and specified thermal properties for the surfaces. The following boundary conditions and assumptions were considered:

- Top surface heat transfer coefficient is 10 W/m²K.
- Bottom surface heat transfer coefficient is 6 W/m²K.
- It is assumed that the side surfaces are insulated.
- It is assumed that thermal conductivity, viscosity, flow density, and the specific heat coefficient remain constant and do not vary with temperature.
- The ambient temperature is 20℃ on both the top and bottom surfaces.

The heat fluxes and temperature distributions on the top and bottom ambient surfaces for supply water temperatures (30/35/40℃) were studied for each pipe location as described in the DLTS. The pipe materials, positions, and the spacing between pipes were also defined according to typical configurations used in underfloor heating systems. And also analysis is performed with the program to determine the correct pipe position on the Y-axis. For these analyses, three positions were selected on the vertical Y-axis, shown in Figure 3, in the DLTS system, 0.001 m, 0.050 m and 0.100 m, respectively.



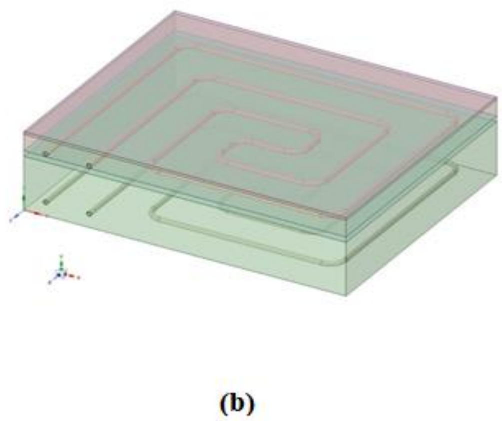


Figure 2. (a) Floor section and (b) isometric numerical view of considered DLTS system [27] ((a) Dikkate alınan DLTS sisteminin zemin kesiti ve (b) izometrik sayısal görünümü)

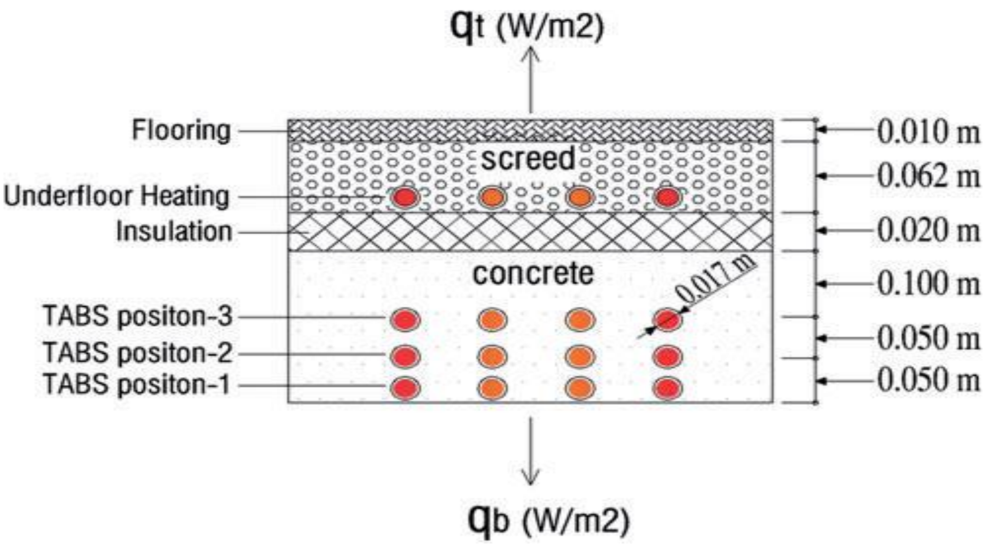


Figure 3. DLTS system's pipe positions 1,2 and 3 (DLTS sisteminin 1, 2 ve 3 numaralı boru konumları)

According to the results of analyses, the situation where the pipe is positioned 0.05 m on the vertical axis is the best position in terms of thermal efficiency. Numerical analyses were performed under steady state conditions. Also, SIMPLE algorithm and standard k-e turbulence model were used in these analyses. Heat fluxes and temperature distributions of the surfaces were investigated at various supply water temperatures (30/35/40°C) for every pipe location, respectively as shown in Table 2.

Table 2. Fluxes and average surface temperatures for every pipe location of TABS at supply water temperatures (30/35/40°C) (Besleme suyu sıcaklıklarında (30/35/40°C) TABS'in her boru konumu için akılar ve ortalama yüzey sıcaklıklar)

	Position-1 (y:0.001 m)			Position-2 (y:0.005 m)			Position-3 (y:0.01 m)		
	T_{inlet} (°C)			T_{inlet} (°C)			T_{inlet} (°C)		
	30	35	40	30	35	40	30	35	40
T_{HF} Average Top surface heat flux (W/m²)	51.5	77.3	103.1	52.2	78.4	104.5	52.1	77.7	103.5
T_S Average Top surface temperature (°C)	25.3	28.0	30.71	25.4	28.1	30.86	25.4	28.1	30.75

In accordance with the EN 1264 standard [29], the maximum surface temperature in the footprint zone is 29°C. From the data in Table 2, it was concluded that a supply water temperature of 40°C is not appropriate for heating, as the average surface temperature surpasses 29°C in all three pipe positions. Average temperature contours and distributions on the top surface for three different pipe locations (1,2 and 3) at supply water temperature of 40 °C are shown in Figures 4-5. The average temperatures show similar distributions and are above the temperature limit of 29 °C in all three locations.

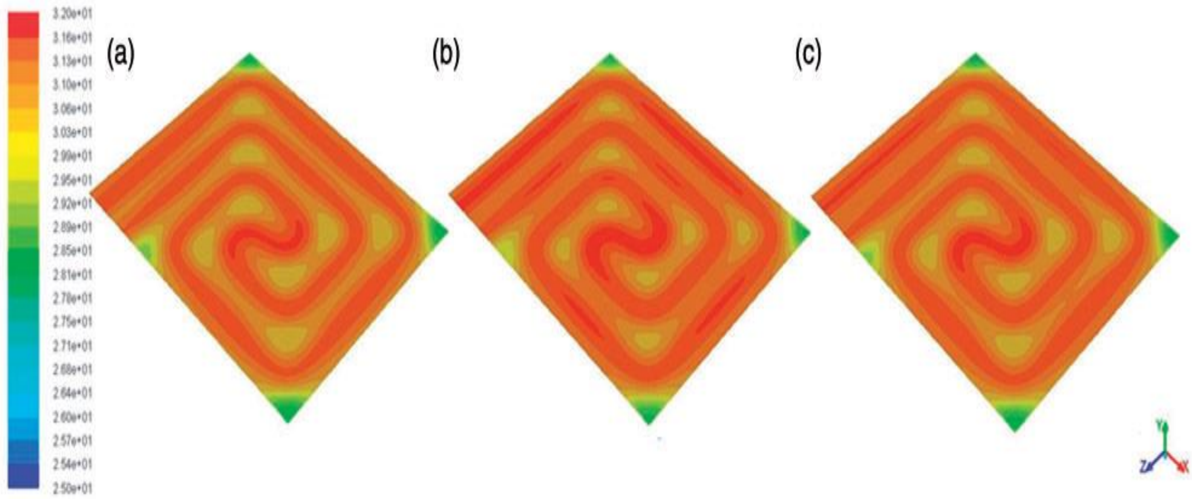


Figure 4. Temperature contours on the top surface for a supply water temperature of 40 °C for three pipe positions (a) 1, (b) 2 and (c) 3 (Üç boru konumu (a) 1, (b) 2 ve (c) 3 için 40 °C'lik bir besleme suyu sıcaklığı için üst yüzeydeki sıcaklık konturları)

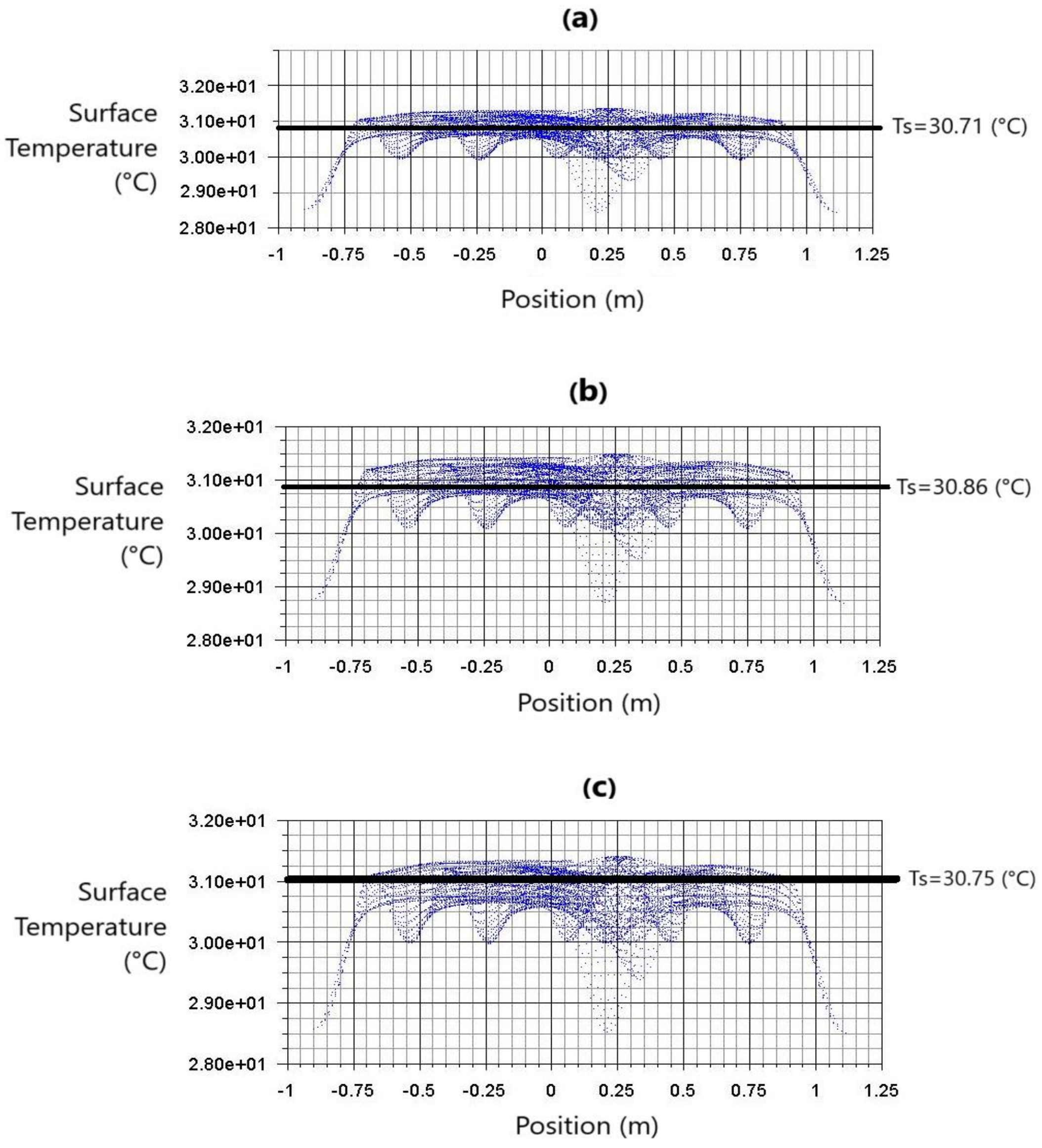


Figure 5. Temperature distributions on the top surface for a supply water temperature of 40 °C for three pipe positions (a) 1, (b) 2 and (c) 3 (Üç boru konumu (a) 1, (b) 2 ve (c) 3 için 40 °C'lik bir besleme suyu sıcaklığı için üst yüzeydeki sıcaklık dağılımları)

Figure 6 shows the optimal pipe positions along the vertical y-axis for different supply water temperatures. The positions giving the maximum heat flux at 40 degrees and 35 degrees supply water temperatures are 0.052 and 0.053 meters, respectively. The pipe position giving the maximum heat flux at 30 degrees supply water temperature is 0.06 meters. Since we want to obtain the maximum heat flux from the reference surface, the positions giving these heat fluxes are accepted as the optimum pipe positions.

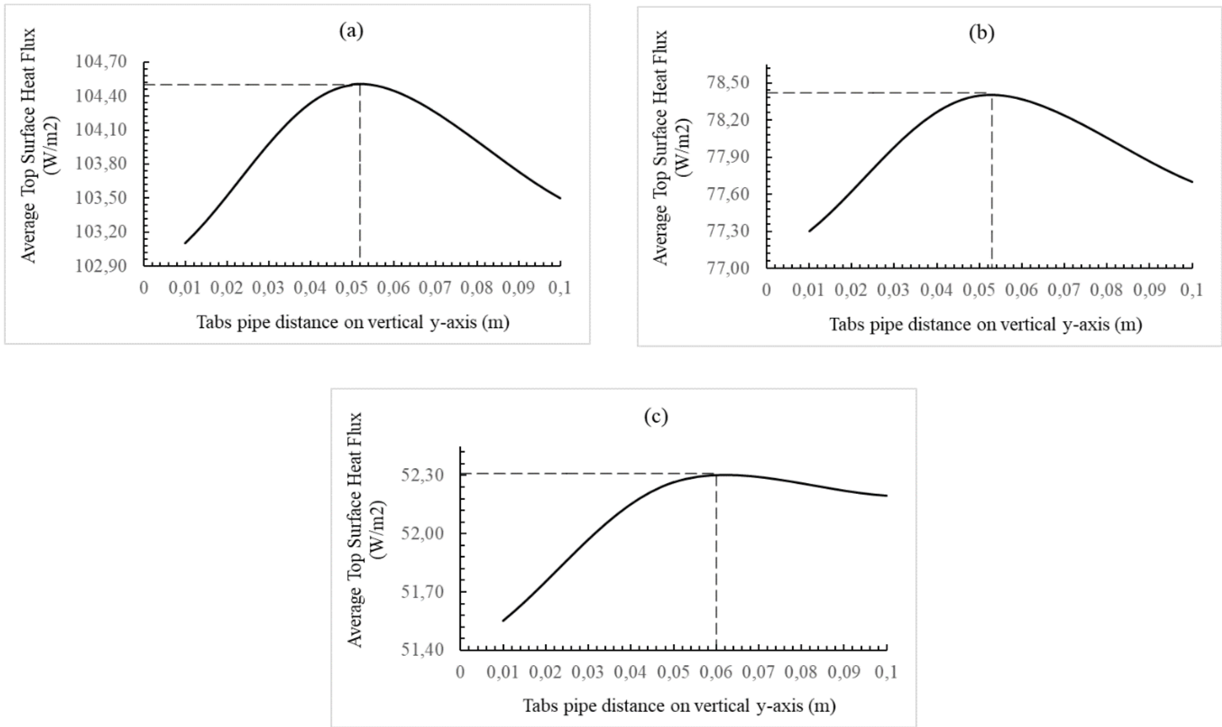


Figure 6. Optimum positions of tabs pipes at different supply temperatures (a) 40°C, (b) 35°C and (c) 30°C (Farklı besleme sıcaklıklarında sekmeli boruların optimum konumları (a) 40°C, (b) 35°C ve (c) 30°C)

Considering the fact that the pipe positions are very close to each other and the difficulty of making precise adjustments in practice, the optimum pipe position was accepted as an average value of 0.05 meters. In this study, this position of the pipe was taken into consideration and the change of the surface temperature according to the supply water temperature was optimized to provide the best thermal comfort and reduce energy consumption.

3.2. Optimization model and solutions in DLTS

(DLTS'de optimizasyon modeli ve çözümleri)

Nonlinear constrained optimization was used as an optimization model in determining the supply water temperature depending on the surface temperature. For the solution, the generalized reduced gradient (GRG) algorithm is used. The GRG algorithm is widely used in engineering for optimization problems and provides reliable results in nonlinear constrained optimization [30-31]. It has proven effective, especially in complex, nonlinear problems where multiple variables require optimization. In this study, the GRG algorithm was chosen to optimize the supply water temperature based on surface temperatures, as this algorithm provides both precise results and a practical solution for engineering applications.

The step-by-step optimization procedure using the GRG algorithm is illustrated in Figure 7. This flowchart summarizes the iterative process applied in determining the optimal supply water temperature, based on surface temperature and thermal comfort constraints. The diagram shows that the PPD-based and supply temperature-based objective functions were solved under relevant comfort class limitations to achieve energy-efficient thermal comfort.

The main idea in the GRG algorithm is to solve the constrained problem by making it unconstrained using the displacement method [32]. In the GRG method, Newton or conjugate gradient method is used to determine the search direction. Also, a Hessian matrix should be used to store data [31].

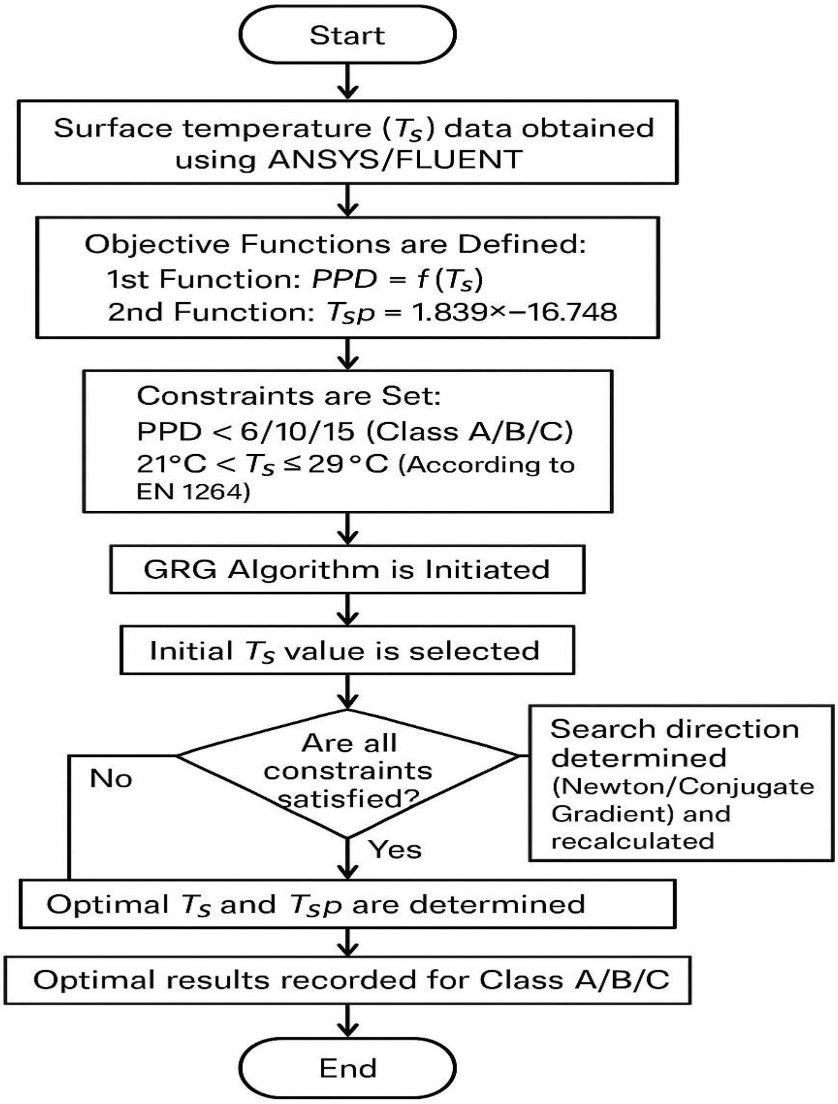


Figure 7. GRG optimization flowchart for supply water temperature (Besleme suyu sıcaklığı için GRG optimizasyon akış şeması)

This study aims to find the optimum values of the supply water temperature for A, B, and C comfort classes according to the specified constraints. For this purpose, two objective functions were used for the solution. To determine the optimum values, non-linear optimization is made with MATLAB and EXCEL Solver by writing objective functions and restrictive parameters.

First objective function is a function of PPD given in Equation 1 depending on the surface temperature (Ts) [33].

$$PPD(T_s) = 100 - 94 \cdot e^{(-1.387+0.118 \cdot T_s - 0.0025 \cdot T_s^2)} \quad (1)$$

The limiting parameters in this function are determined according to the comfort classes in Table-1. Namely: PPD <6 for Class A, PPD <10 for Class B, and PPD <15 for Class C. Also, another limiting parameter is T_s, and PPD is a sign constraint as it cannot be negative. If $T_s \geq 0$ and PPD ≥ 0 it is defined as.

Second objective function supply water temperature (T_{sp}) is a function that depends on the surface temperature. For the DLTS system designed with the FLUENT/ANSYS program, this function is curved to the change values of the surface temperature and the supply water temperature (Figure 8). Establishing a objective function for supply water. The supply water temperature was drawn from the parametric equation obtained without fitting the curve in terms of curve fitting, and it was obtained as in Equation 2 depending on the surface temperature. This equation obtained is defined as the second objective function in this study.

$$T_{sp}(T_s) = 1.839 . T_s - 16.748 \quad (2)$$

The limiting parameter for this second objective function is the maximum value of the surface temperature according to thermal comfort conditions. The limits of maximum surface temperatures according to EN 1264-2 are given in Table 3 [29]. Accordingly, the maximum surface temperature at the first zone, which is the footed zone, is 29°C. Hence the first limiting parameter will be $T_s \leq 29$ [29]. The second constraint is that the room temperature should be 20°C, so the surface temperature should exceed this temperature. Therefore, the second limiting parameter is $T_s > 21$ determined as.

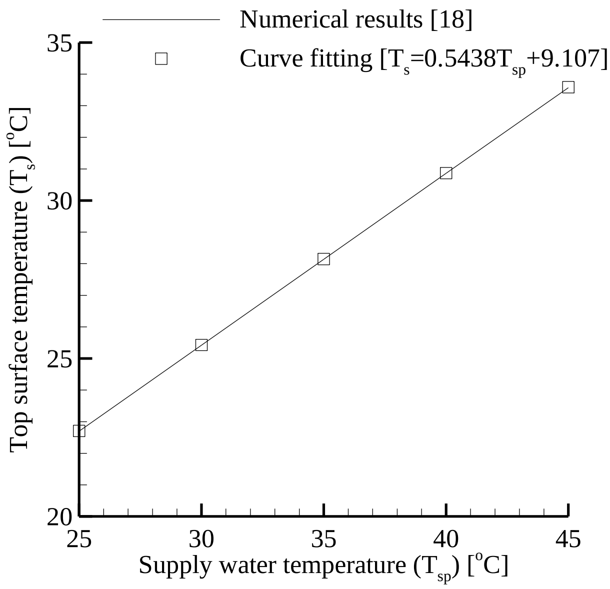


Figure 8. Change of surface temperature depending on the supply water temperature (Besleme suyu sıcaklığına bağlı olarak yüzey sıcaklığının değişimi)

Table 3. Maximum surface temperatures according to EN 1264-20 [29] (EN 1264-20'ye göre maksimum yüzey sıcaklıkları)

Regions	Maximum Surface Temperature [°C]
TYPE-1. ZONE Footed areas	29
TYPE-2. REGION Wet areas (Bathroom-WC etc.)	33
TYPE-3. ZONE Non-footed edge areas	35

4. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

PPD is equal to 5.49% in case PMV value is zero which is ideal and representing thermal neutrality. Surface temperature and supply water temperatures corresponding to these values are calculated from Equations 1 and 2 and the results are shown in Table 4. For the system designed in this study for the most ideal ambient conditions, the surface temperature is 23.6°C, while the supply water temperature is 26.66°C.

Table 4. Thermal neutrality surface and supply water temperatures for the condition (Termal denge koşulu için yüzey ve tedarik suyu sıcaklıkları)

Surface Temperature [°C]	Minimum PPD Value [%]	Supply Water Temperature [°C]
23.6	5.49	26.66

Unlike single-layer TABS studies, the DLTS system in this study demonstrated enhanced thermal comfort and energy efficiency by optimizing pipe positioning and water supply temperature. Previous studies on single-layer systems, such as those conducted by Simmonds [11] and Baumgartner & Brühwiler [12], have shown limited thermal performance in similar conditions.

The value of maximum supply water and surface temperatures according to different comfort classes is given in Table 5. In optimization, when maximizing values are found in response to objective functions and restrictive parameters, the maximum surface temperatures against 6 and 10, which are the maximum value of PPD for comfort classes A and B, are calculated as approximately 25.070 and 28.022, while the supply water temperatures are calculated as approximately 29.362 and 34.786, respectively. However, since the surface temperature corresponding to the maximum PPD value of 15 for the C comfort class exceeds the thermal comfort condition of 29°C, the maximum PPD value for the C comfort class in the DLTS that was investigated in this study should be taken as approximately 12.136. The maximum surface temperature corresponding to this value is 29°C and the supply water temperature is 36.583°C.

Table 5. Change of Maximum Supply Water and Surface Temperature according to different comfort classes (Farklı konfor sınıflarına göre Maksimum Besleme Suyu ve Yüzey Sıcaklığının Değişimi)

Comfort class	Max. Surface Temperature [°C]	PPD Value [%]	Maximum Supply Water Temperature [°C]
A	25.07	5.99	29.36
B	28.02	9.99	34.78
C	29	12.13	36.58

As a result of the analysis made according to the restrictive parameters, minimum surface temperature, minimum supply water temperature, and corresponding PPD values for comfort classes A, B and C are given in Table 6. While the minimum supply water temperature in A comfort class is 23.96°C, in B and C comfort class, the restrictive parameter Ts>21, the minimum supply water temperature that satisfies this requirement is 22°C. The PPD value for both classes is approximately 7% and it complies with the standards.

Table 6. Variation of minimum supply water and Surface temperature according to different comfort classes (Farklı konfor sınıflarına göre minimum besleme suyu ve yüzey sıcaklığının değişimi)

Comfort class	Min. Surface Temperature [°C]	PPD Value [%]	Minimum Supplyf Water Temperature [°C]
A	22.13	5.99	23.96
B	21.06	6.99	22
C	21.06	6.99	22

While traditional TABS configurations often necessitate higher supply water temperatures to maintain thermal comfort, the optimised DLTS system in this study achieves thermal comfort at a significantly lower supply water temperature, thereby demonstrating the potential for substantial energy savings in comparison to the findings of earlier research, for example Zaheer-uddin et al. [15].

Figure 9 displays the change of supply water temperature and PPD values according to surface temperature for different comfort classes. As indicated by the figure, since the maximum surface temperature for the C comfort class exceeds 30.1°C, which is the thermal comfort condition for surface temperature based on EN 1264-2 standard [29], the maximum surface temperature will be 29°C for this comfort class. Although the minimum surface temperature is around 17.4°C according to the graph, since this value does not meet the restrictive parameter Ts≥21, the minimum surface temperature is 21.06°C. On the other hand, the minimum supply water temperature is 21.06°C. The maximum supply water temperature is 36.58°C. As per the EN

1264-2 standard, since the maximum surface temperature for wet areas and non-footed edge areas can be 33 and 35°C, respectively, in this case, the maximum supply water temperature can rise to 38.63 ° C (Table-3). Minimum and maximum surface temperatures for comfort class B are 21.06 and 28.02°C, respectively. While the minimum value of the supply water temperature is 22°C, the maximum value is 34.78°C. In comfort class A, the maximum and minimum temperatures of the surface are 22.13°C and 25.07°C, respectively. While the value of the minimum supply water temperature is 23.96°C, the maximum value is 29.36°C.

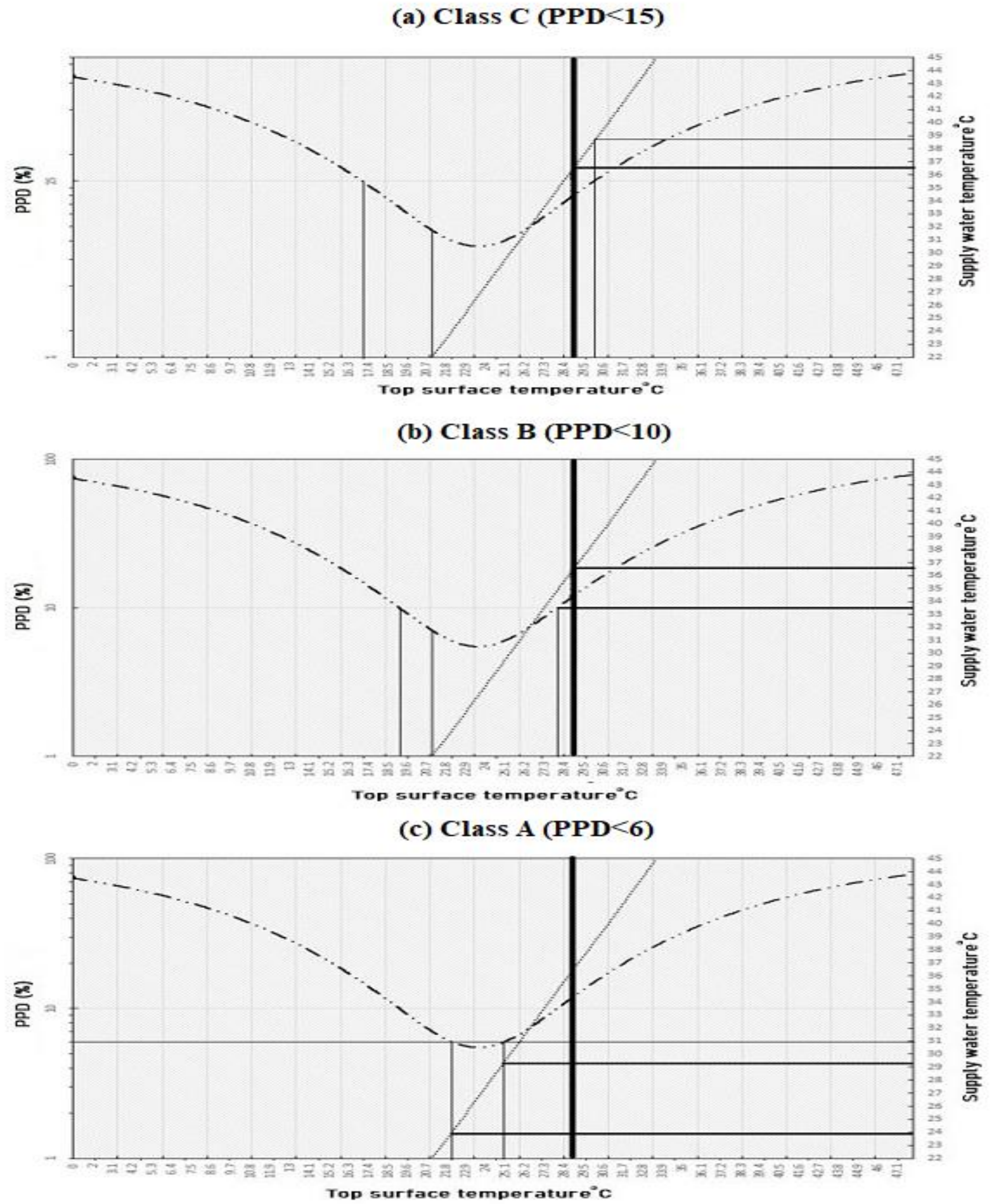


Figure 9. Optimum and limit values for A, B, and C comfort classes (A, B ve C konfor sınıfları için optimum ve sınır değerler)

Table 7 shows the values obtained in heating mode for A, B, and C comfort classes. According to this table, room temperature limit values corresponding to PMV values of A, B, and C classes are given respectively. Minimum and maximum values are 21 and 23°C for comfort class A, 20 and 24°C for comfort class B, and 19 and 25°C for comfort class C. The table also gives the surface temperatures corresponding to the PMV value for each comfort class and the corresponding supply water temperatures. For the proposed double-layer TABS system, the minimum supply water temperature is 22°C and the maximum supply water temperature is 36.6°C. The optimum supply water temperature for all three classes is 26.66°C and the optimum surface temperature is 23.60°C. In the double-layer TABS system, ideal values for all three classes can be determined according to this table and system design can be made.

Table 7. A, B, and limit values in heating mode in comfort classes C (Konfor sınıfları C'de ısıtma modunda A, B ve sınır değerleri)

	Class A	Class B	Class C
Comfort zone	-0.2 < PMV < 0.2	-0.5 < PMV < 0.5	-0.7 < PMV < 0.7
Indoor room temperature (T_r) Range (°C)	$21 < T_r < 23$	$20 < T_r < 24$	$19 < T_r < 25$
Top surface temperature (T_s) range (°C)	$22.1 < T_s < 25.1$	$21.1 < T_s < 28$	$21.1 < T_s < 29$
Supply water temperature (T_{sp}) range (°C)	$24 < T_{sp} < 29.4$	$22 < T_{sp} < 34.8$	$22 < T_{sp} < 36.6$
Optimum supply water temperature (T_{sp}) (°C)	26.66	26.66	26.66
Optimum top surface temperature (T_{sp}) (°C)	23.60	23.60	23.60

Our study aligns with ASHRAE and ISO thermal comfort criteria, similar to prior research by Stoffel et al. [23], but provides improved results with PPD values consistently under 12% for Class C, which is more favorable compared to the typical range found in single-layer TABS studies.

A significant finding of this study is the demonstration of the energy-saving potential of the DLTS system in comparison to traditional single-layer TABS systems. As demonstrated in Table 7, the DLTS system attains optimal thermal comfort under Class A comfort conditions with a supply water temperature of a mere 26.66°C. Conversely, single-layer TABS systems generally necessitate higher supply water temperatures, typically ranging from 30 to 35°C, to attain comparable levels of comfort. This finding indicates that the DLTS system, with its reduced operating temperature, exhibits reduced energy consumption and enhanced system efficiency.

The DLTS system exhibits a double-layer structure that offers distinct advantages over the single-layer system. The former facilitates more even vertical heat distribution and a more uniform surface temperature distribution. This structural feature serves to reduce local overheating or cooling, thereby enabling more efficient heat transfer and more precise control of occupant comfort. Subsequent to analyses conducted with FLUENT/ANSYS, an optimisation study employing the GRG algorithm has evidently demonstrated that DLTS systems have the capacity to meet comfort criteria with minimal thermal input. The findings indicate that DLTS systems are a more efficient and sustainable alternative to single-layer systems in building applications where energy savings and thermal comfort are priorities.

5. CONCLUSIONS AND SUGGESTIONS (SONUÇLAR VE ÖNERİLER)

The DLTS system presents a promising alternative to traditional heating and cooling systems, offering a solution with lower energy consumption and higher comfort levels. This study introduces an innovative approach by optimizing the Double Layered Thermally Activated Building System (DLTS) for superior thermal comfort and energy efficiency compared to traditional single-layer systems. The supply water temperature optimization process was evaluated in light of the comfort limits set by ASHRAE 55, ISO 7730, and EN1264-2 standards for the DLTS system. The comfort criteria for classes A, B, and C were calculated, and the minimum, maximum, and optimum values for supply water and surface temperatures were determined. The main findings of the study can be summarized as follows:

- **Supply Water Temperatures:** It was observed that the maximum supply water temperature is 36.58°C, and the minimum supply water temperature is 22°C. The maximum surface temperature was found to be 29°C, while the minimum surface temperature was 21.06°C.

- **Optimum Values:** For all three comfort classes (A, B, and C), the optimum supply water temperature was calculated to be 26.66°C, and the optimum surface temperature was 23.60°C for achieving neutral thermal sensitivity. These values are critical for ensuring the highest level of indoor thermal comfort.
- **PPD (Predicted Percentage of Dissatisfied)**: For class C, the calculated PPD value for the DLTS system was found to be <12.14. This result indicates that the low-temperature system provides a sufficiently high level of comfort and ensures user satisfaction effectively.
- **Optimum Pipe Position:** The optimum positioning of the pipes was determined to be 0.05 meters along the vertical y-axis. This positioning is a crucial design element that enhances both the system's efficiency and comfort.

This study highlights the potential of the Double Layered Thermally Activated Building System (DLTS) to optimize thermal comfort and supply water temperatures, which significantly impacts energy efficiency and user satisfaction in buildings. Moreover, determining the optimum temperature values and pipe positioning are critical factors to consider in the future design of such systems. The optimized supply water temperatures and pipe positioning identified in this research provide valuable guidance for the future implementation of DLTS systems in both new construction and retrofitting projects. By achieving thermal comfort with lower energy consumption, DLTS systems offer a sustainable alternative for reducing buildings' carbon footprints.

Application Areas and Building Utilization

The optimized DLTS design from this study is anticipated to have broad application potential in commercial and residential buildings where energy efficiency and thermal comfort are critical. Integration of DLTS with low-temperature heating systems can make a significant contribution to reducing energy costs, making it an ideal solution for buildings that aim to meet high energy efficiency and green building standards.

Applicability to Existing Buildings

In addition to new construction projects, DLTS systems can also be integrated into existing buildings. Particularly in ground-level or floor zones, implementing these systems can improve indoor comfort levels while also reducing energy consumption. The applicability of DLTS systems to existing buildings presents a valuable opportunity for renovation projects, where the energy efficiency of older buildings can be improved to align with modern buildings.

Suggestions for Future Studies

Future studies could explore the performance of DLTS systems under various climatic conditions and for different types of buildings to expand their applicability. Additionally, integrating DLTS with advanced control algorithms could further improve energy savings and occupant comfort, establishing DLTS as a key component in energy-efficient building designs.

Environmental Impact and Energy Saving Potential

Using optimized water temperatures in DLTS systems has the potential to provide substantial energy savings and reduce the carbon footprint. The widespread adoption of these systems could contribute to environmental sustainability in the building sector. Expanding the use of DLTS systems to achieve energy efficiency would offer economic and environmental benefits and support sustainable building practices.

In conclusion, the DLTS system presents a promising alternative to traditional heating and cooling systems by offering lower energy consumption and higher comfort levels. The study's findings support the applicability of DLTS systems in new construction projects and renovations. By achieving energy savings, DLTS systems provide a sustainable alternative for reducing the carbon footprint of buildings. Future studies exploring the performance of DLTS under various climate conditions would further contribute to expanding DLTS applications across the building sector.

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The authors of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Oğuzhan ÇALIŞIR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Kavramsallaştırma, Veri düzenleme, Biçimsel analiz, Araştırma, Metodoloji, Doğrulama, Görselleştirme, Yazma – orjinal taslak, Yazma – inceleme ve düzenleme.

Müjdat ÖZTÜRK: Data curation, Formal analysis, Methodology, Validation, Writing – original draft; Writing – review & editing.

Veri düzenleme, Biçimsel analiz, Metodoloji, Doğrulama, Yazma – orjinal taslak; Yazma – inceleme ve düzenleme.

Gamze GENÇ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Kavramsallaştırma, Veri düzenleme, Biçimsel analiz, Araştırma, Metodoloji, Denetim, Doğrulama, Görselleştirme, Yazma – orjinal taslak, Yazma – inceleme ve düzenleme.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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