



PERFORMANCE OF SOLAR ENERGY DRIVEN FLOOR HEATING SYSTEM

Cüneyt KURTAY*, İbrahim ATILGAN** and Ö. Ercan ATAER***

*Gazi Üniversitesi, Mühendislik Mimarlık Fakültesi Mimarlık Bölümü
06570 Maltepe, Ankara, kurtay@gazi.edu.tr

**Gazi Üniversitesi, Mühendislik Mimarlık Fakültesi Makine Mühendisliği Bölümü
06570 Maltepe, Ankara, atilgan@gazi.edu.tr

***Gazi Üniversitesi, Mühendislik Mimarlık Fakültesi Makine Mühendisliği Bölümü
06570 Maltepe, Ankara, oataer@gazi.edu.tr

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Abstract: Using solar energy an office is heated from the floor and a thermal comfort analysis is performed for Ankara conditions. Solar energy is collected by flat-plate collectors in a storage tank. The thermal comfort analysis of the office is performed using Fanger's method. In this method the thermal comfort is affected by environmental and individual parameters; air velocity, humidity, temperature, radiation temperature, activity and cloth resistance. Measurements are taken at 0.2 m, 0.6 m, and 1.0 m heights beside floor temperature. The experimental results and the individual data are used to calculate the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). A computer program is written in FORTRAN to calculate these parameters using the experimental, individual data and the results are presented as PMV diagrams. The results indicate that the thermal comfort can be provided with such a heating system. The PMV values range between -2.00 to 2.00.

Keywords: Solar heating, thermal comfort, floor heating

GÜNEŞ ENERJİSİ İLE DÖŞEMEDEN ISITMA SİSTEMİNİN PERFORMANS ANALİZİ

Özet: Bu çalışma, güneş enerjisinden yararlanarak Ankara şartlarında döşemeden ısıtma sisteminin projelendirilmesi ve ısı konfor şartlarının incelenmesini içermektedir. Güneş enerjisi, düzlem plakalı kolektörler kullanılarak elde edilmiş ve depolanmıştır. Çalışmada Fanger yöntemi kullanılarak sistemin ısı konfor şartları deneysel olarak incelenmiştir. Bu yöntemde ısı konfor şartlarını etkileyen değişkenler çevresel ve kişisel değişkenler olmak üzere iki ana grupta toplanır. Aktivite ve giysi değerleri kişisel değişkenler; hava hızı, nem, sıcaklık ve ışımaya sıcaklığı çevresel değişkenlerdir. Analizde döşeme sıcaklığı, döşemeden 0,2 m, 0,6 m ve 1,0 m yükseklikte çevresel değişkenler ölçülmüştür. Deneysel veriler kullanılarak FORTRAN dilinde yazılan bilgisayar programı yardımı ile Önceden belirlenen ortalama oylama (PMV) ve önceden belirlenen hoşnutsuzluk oranı (PPD) değerleri hesaplanmış ve grafik olarak sunulmuştur. PMV değerleri -2.00 ile + 2.00 arasında değişmektedir. Sonuçlar deneydeki gibi yöntemle ısı konforun sağlanabileceğini göstermiştir.

Anahtar Kelimeler: Güneş enerji ile ısıtma, ısı konfor, döşemeden ısıtma

Nomenclature

A_{DU}	Du-Bois surface area(m^2)
f_{cl}	the ratio of the surface area of the clothed body to the surface area of the nude body
h_c	Heat transfer coefficient (W/m^2K)
I_{cl}	Thermal resistance from skin to outer surface of the clothed body (clo)
M	Metabolic rate (W)
η	Mechanical efficiency
P_a	vapour pressure in ambient air (mmHg)
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
T_a	Air temperature ($^{\circ}C$)
T_{in}	Collector inlet temperature ($^{\circ}C$)
T_m	Mean water temperature ($^{\circ}C$)

T_{out}	Collector exit temperature ($^{\circ}C$)
T_{mrt}	Mean radiation temperature ($^{\circ}C$)
T_{cl}	Mean temperature of outer surface of clothed body ($^{\circ}C$)
v	Relative air velocity (m/s)

INTRODUCTION

It is clear that the human being should be in thermal comfort to study efficiently in their office. In order to establish favourable indoor thermal environment, human thermal comfort should be evaluated. Recently radiant floor heating applications have increased significantly in Europe, and new residential buildings have floor heating systems. The basic components of the space heating systems using floor heating system are

similar to those of domestic water heating systems. The floor heating systems, driven by solar energy operate at lower temperatures (that is less than 32°C), and heat transfer rate into the space is by radiation and convection. (Athienitis and Chen, 2000)

Sattari and Farhanieh, (2006) considered transient conduction, convection and radiation heat transfer mechanisms, and analyzed the thermal performance of radiant systems in buildings by using a finite element method. Yeo and others (2003) investigated the changes and recent energy saving potential of residential heating in Korea, and shown that modern apartment buildings with hot water radiant floor heating yield less heat loss due to the tighter envelope, but also yield higher energy consumption.

Becker and Paciuk (1993) presented the methodology developed to investigate the various effects of different heating patterns on the overall thermal performance of residences, that does not receive solar gains. Bouchlaghem (1999) developed a computer program which simulates the thermal performance of the building taking into account design variables related to the buildings envelope, but also applies numerical optimization techniques to determine the optimum design variables.

Martinez, et. al. (2005) analysed the performance of a residential solar heating system in Murcia in Spain, and use the recorded data to estimate the performance of the system. Badran and Hamdan (2004) make a theoretical and experimental study for floor heating system using solar collectors. Also they studied a similar system using solar ponds under the same local conditions.

Zhai, et. al., (2007) built a solar system capable of heating, cooling, natural ventilation and hot water supply in Shanghai. The system contains 140 m² solar collector arrays, two adsorption chillers, floor radiation heating pipes, finned tube heat exchangers and a hot water storage tank of 2.5 m³. It is used for heating in winter, cooling in summer, natural ventilation in spring and autumn, hot water supply in all the year for 460 m² building area. After 1 year operation, it is confirmed that the solar system contributes about 65% of the total energy of the involved space for the weather conditions of Shanghai. Heat is transferred from the pipes to the surface of the floor and it is transferred to the room by convection.

Atmaca, et. al., (2007) investigate the local differences between body segments causes by radiant temperature and analyzed the interior surface temperatures for different wall and ceiling constructions with their effect on thermal comfort. Dalamagkidis, et. al., (2007) studied the comfort in buildings with minimal energy consumption. Nicol and Humphreys (2007) studied the maximum temperatures in European office buildings to avoid thermal discomfort. This work defines comfortable conditions and the range of acceptable temperature. Fernandez and Gonzalez, 2007 analysed

the thermal performance and comfort conditions produced by five different passive solar heating strategies in the United States Midwest.

This study analyses the thermal comfort in a office with floor heating system for Ankara. A solar heating system is designed and constructed using flat-plate solar collectors. For winter conditions the thermal comfort is performed using the method proposed by Fanger (1970). The floor heating area of the office is about 23 m² and the flat plate collectors are used and mounted to the roof of the building with a slope of 35°. The PMV values at 0.2 m, 0.6 m and 1.0 m from the floor and the mean PPD values are calculated. The iso-PMV curves are drawn for two different clo-values. Results at different levels are compared and evaluated.

EXPERIMENTAL STUDY

The building is located in Ankara, and the experiments were performed during the winter time of the year 2007. The room is located to corner of the second floor of the multi-store building. Its windows are looking to the south-east. The space is intended as an office, and dimensions of the office are 630 cm x370 cm and 335 cm height. The walls of the office are made of brick and both side of it are covered by plaster. The heat loss of the office is calculated as 3.10 kW and the outer design temperature of Ankara is taken as -12°C. There were three people in the office and they were sitting during the experiments. Each experiment took about 3 hours. This may cause some deviations from the expected data. During the experiments the direct radiation at the daytime is changed. This affects the temperature and therefore the PMV values.

The floor heating system using solar energy is designed, and the working parameters of the system are given in Table 1. The diagram of the floor heating system is shown in Fig.1. The selective surface of the collectors was made of copper and painted with mat black.

Table 1. Properties of the solar heating system.

Properties	Zone A (Near the window)	Zone B (Near the door)
Water inlet temperature	50 °C	50 °C
Water exit temperature	40 °C	22 °C
Comfort area	8 m ²	12 m ²
Heat transfer rate	1376 W	624 W
Volumetric flow rate	3.7 x 10 ⁻⁵ m ³ /s	0.583 x 10 ⁻⁵ m ³ /s
Floor temperature	35 °C	25 °C
Pressure drop	139 mbar	6.5 mbar
Axial distance between pipes	10 cm	20 cm
Length of pipe	80 m	60 m

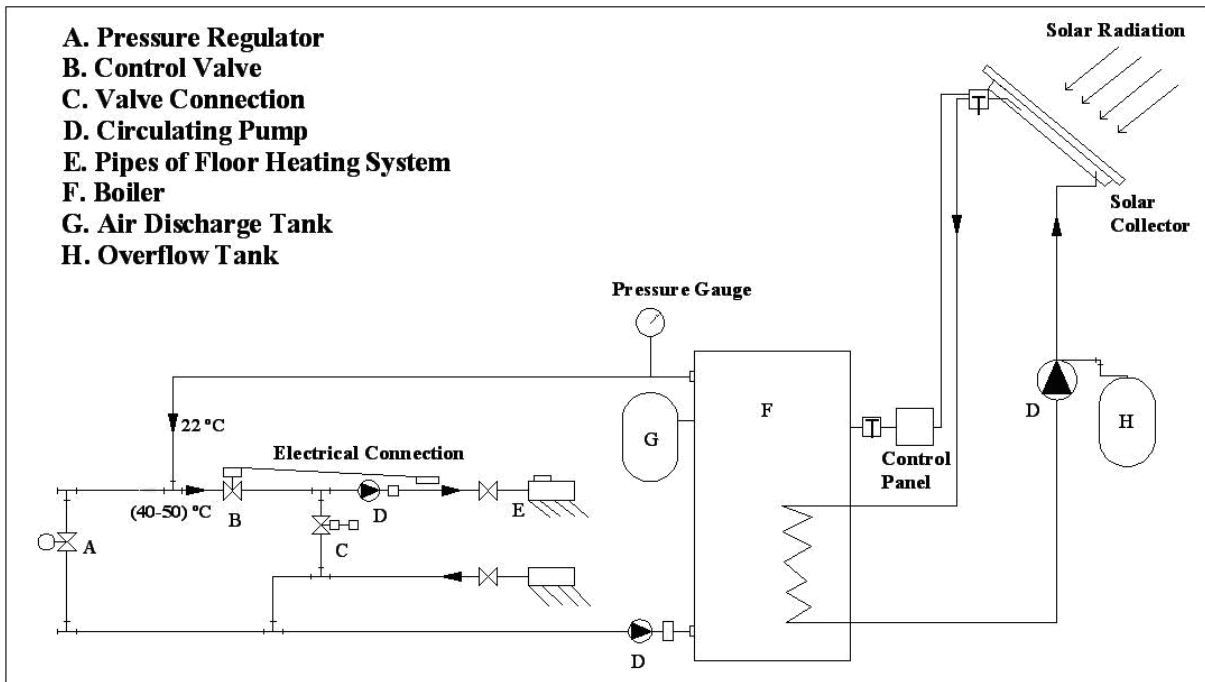


Figure 1 The schematic diagram of the floor heating system

The hot water is collected in a storage tank of 0.20 m³ capacity and insulated with the glass wool of 5 cm thickness. The storage tank works as counter flow heat exchanger. An electrical resistance heater of 2 kW capacity is used as heat source for the conditions in which solar energy is not sufficient. The control panel is used to compare the water temperature of the storage tank and water input temperature to keep it above 5°C.

The hot water is circulated in 140 m long plastic water pipe under the floor. Its outer diameter is about 16 mm and 2 mm thick. Plastic combs are used to keep the distance between the pipes constant as shown in Fig. 2. Polystyrene insulation material of 3 cm thick and a nylon layer is used below the pipes. The pipes are covered by 3 cm thick concrete, and laminate floor material is used as finishing layer. Near the windows the distance between the pipes are narrow as shown in Fig. 2.a. This is because of the high heat losses near the windows.

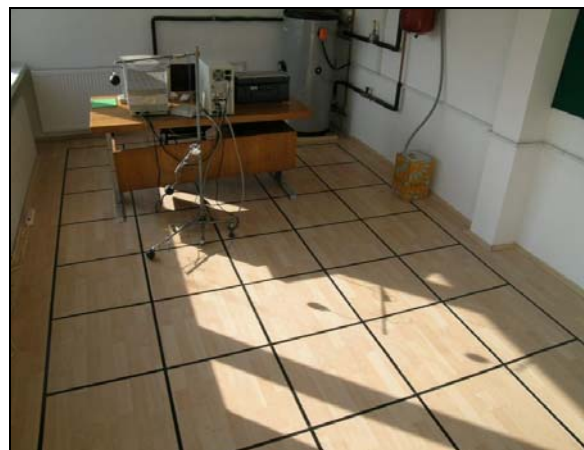
The occupied zone of the office is divided into 55x55 cm squares as shown in Fig. 2.b. and totally there are 50 squares on the floor. Measurements are taken at the centre of each square for three heights above the floor level. In order to obtain reasonable data in all experiments measurements are taken over the period of 4 min. The air temperature, the mean radiant temperature, the air velocity and the relative humidity are measured at each measuring points.

The tank inlet and exit temperatures are measured, and the mean water temperature in the tank is calculated by $T_m = (T_{in} + T_{out}) / 2$. The variation of outer air temperature, the inlet and outlet water temperatures are shown in Fig.3.

Fanger (1970) used Predicted Mean Vote (PMV) for the thermal comfort and proposed the following equation for the PMV:



(a)



(b)

Figure 2. Installation of water pipe and finishing.

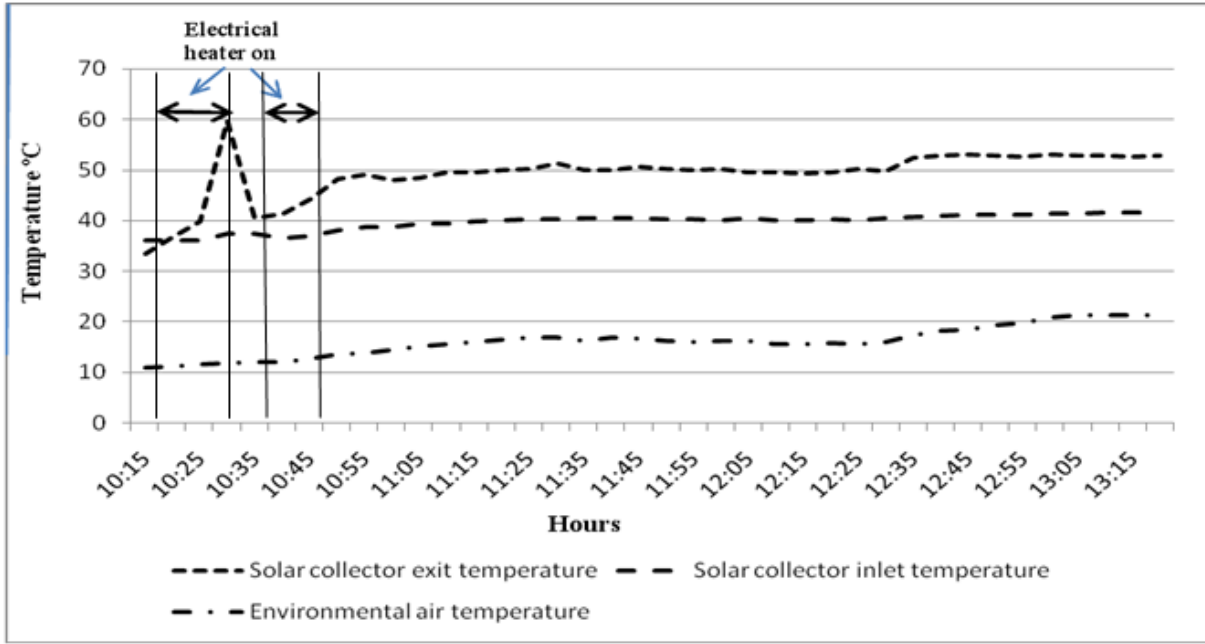


Figure 3. Environmental air temperature, and solar collector inlet and collector exit temperatures of the water.

$$PMV = (0.352e^{-0.042(M/A_{Du})} + 0.032) \left[\frac{M}{A_{Du}}(1-\eta) - 0.35 \left[43 - 0.061 \frac{M}{A_{Du}}(1-\eta) - p_a \right] - 0.42 \left[\frac{M}{A_{Du}}(1-\eta) - 50 \right] - 0.0023 \frac{M}{A_{Du}}(44 - p_a) - 0.0014 \frac{M}{A_{Du}}(34 - T_a) - 3.4 \cdot 10^{-8} f_{cl} [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] - f_{cl} h_c (T_{cl} - T_a) \right] \quad (1)$$

Where h_c is the heat transfer coefficient and defined as

$$h_c = 2.05(T_{cl} - T_a)^{0.25} \Rightarrow 2.05(T_{cl} - T_a)^{0.25} 10.4\sqrt{v} \quad (2)$$

$$h_c = 10.4\sqrt{v} \Rightarrow 2.05(T_{cl} - T_a)^{0.25} (10.4\sqrt{v}) \quad (3)$$

Equation (2) is used when the air velocity is less than 0.1 m/s, and Equation (3) is used when the air velocity is greater than 0.1 m/s. Metabolic rate, mechanical efficiency and relative velocity of the still air are taken from Fanger (1970) and given in Table 2.

On the other hand Predicted Percentage of Dissatisfied (PPD) is defined as;

$$PPD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (4)$$

Clothing ensemble is one of the environmental factors which effect the thermal comfort. There are two parameters in the comfort equation related with the clothing ensemble; these are I_{cl} , thermal resistance of the clothing and f_{cl} , the ratio of the surface area of the clothed body to the surface area of the nude body. The

data for different clothing ensembles in winter conditions are taken from Fanger (1970) and given in Table 3.

Table 2. Metabolic rate of some office work (Fanger,1970)

Activity	Metabolic rate (W/m ²)	Mechanical efficiency (η)	Relative Velocity in still Air (m/s)
Reading by sitting	55	0	0,05
Writing	60	0	0,05
Computer using	65	0	0,05

Table 3. Data for different clothing ensembles to winter conditions for Office Work.(Fanger, 1970)

Clothing ensemble	I_{cl} (clo)	
Shirt, trousers, socks, shoes, single ply poplin jacket.	0.9	1.15
For man; Shirt, trousers, and jacket. For woman; Shirt, skirt and jacket	1.2	1.15
Long sleeves cotton shirt, wool socks, shoes, jacket and vest.	1.5	1.15-1.2

RESULTS

Properties of floor heating system are given in Table 1. The results of the experiments done on 9th of February, 2007 are presented. Variation of environmental temperature and solar heat flux with time during the experiments are given in Fig. 4. The drop on the solar heat flux after 11.35 a.m. is due to cloudy weather. The increase on the environmental temperature also stops until at 12.15 p.m. Figure indicates that the environmental conditions were not constant during the experiments.

The average solar heat flux and average value of environmental temperatures are also shown in Fig. 4.

The air temperatures are measured by thermocouples and the mean radiant temperature is measured by the globe thermometer. The globe thermometer is constructed by placing a thermocouple to the centre of the sphere. The sphere is painted by matt black paint with high absorptivity and then calibrated (Fanger, 1970).

The air velocities are measured as less than 0.1 m/s and the analogue data is converted to the digital data and stored in a computer. A computer program is written in FORTRAN, and using the measured values the PMV for each measuring point at three heights are calculated using Equations (1) and (2). For each location the PPD values are also determined using Equation (4) and their mean values are given in Table 4.

Table 4. Mean PMV and Mean PPD values for different levels.

Distance from the floor	Mean PMV Thin I_{cl}	Mean PMV Thick I_{cl}	Mean PPD Thin I_{cl}	Mean PPD Thick I_{cl}
0.2 m	0.38	0.39	15.57	17.51
0.6 m	0.24	0.20	14.21	15.81
1.0 m	0.34	0.33	15.22	17.41

The floor temperatures are measured by standard type compact infrared thermometer. The iso-temperatures of the floor are measured and given in Fig.5. The iso-PMV values at 0.2 m, 0.6m and 1.0 m are drawn and given in Figs 6, 7 and 8 are for thick clothes respectively. The thin and thick clothing ensembles are given in Table 3.

CONCLUSIONS

The PMV-values are calculated by using the thin and thick clo-values, and the activity level given in Table 2 and Table 3 for the winter conditions respectively

Fanger,1970. As shown in Fig.5 the surface temperatures of the floor near windows are higher than the inner regions of the room. This is because of the lengths of the pipes are longer near the windows. Experiments are performed during the noontime and the comfort conditions are affected by the direct solar radiation, though the windows. The maximum floor temperature measured is about 29.5°C and it does not exceed the permissible floor temperature shown in Fig. 5.

On the figures of iso-PMV values the dark regions indicate the low PMV values at which comfort conditions are not provided. According to Fanger's method when the PMV values approaches to zero value, the thermal comfort is provided. The comparison of Iso-PMV lines for thin clo-values at 0.20m., 0.60 m. and 1.00m. with Figs. 6, 7 and 8 indicates that for the thick clothes we have slightly better comfort conditions than the thin clothes. This is because of the difference between the clo-values and the ratio of the surface area of the clothed body to the surface area of the nude body shown in Table 3. This discussion can be extended to all levels. When the clothes are thick the comfort conditions are better than the thin clothes at 0.2 m, 0.6 m and 1.00 m levels. On the other hand the PMV values are increasing at high levels, it means better thermal comfort conditions are provided at 1.0 m than 0.2 m as seen in the Fig. 6 and Fig. 8 for thick clothes.

The PMV values calculated for the office are not homogeneous, and it changes between -1.00 to 1.33 for the thick ensemble given in Fig.6 at the level of 0.20 m. The corresponding mean PPD value is 17.51 for thick cloth as shown in Table 4. This value of PPD indicates that the thermal comfort is not provided at 0.20m. The uncertainty of the PMV values is calculated as ± 0.04 percent.

As indicated in figures given above the thermal field in the office is not uniform. Then, the PMV of course will not be the same over the occupied zone. As an example the calculated PMV values for 0.60 m from the floor level for two different clothing ensembles are given in Iso-PMV lines for thin clo-values at 0.60m and Fig. 7. Comparison of these two figures shows that the PMV values of thick clothing given in Fig. 10 are higher than the thin clothing. Similar results are obtained for other levels of measurements given in Iso-PMV lines for thin clo-values at 1.00m and Iso-PMV lines for thick clo-values at 1.00m. (Fig.8)

It is impossible to satisfy all people in a large group sharing a collective climate. Even with a perfect environmental system, which creates absolutely uniform conditions in the occupied zone, one can not attain a Predicted Percentage of Dissatisfied (PPD) value lower than 5% for similar clothed people and in the same activity.

Martinez, et. Al., (2005) has shown that 20% of the energy required was provided from solar energy during the months of January and February. In our study about

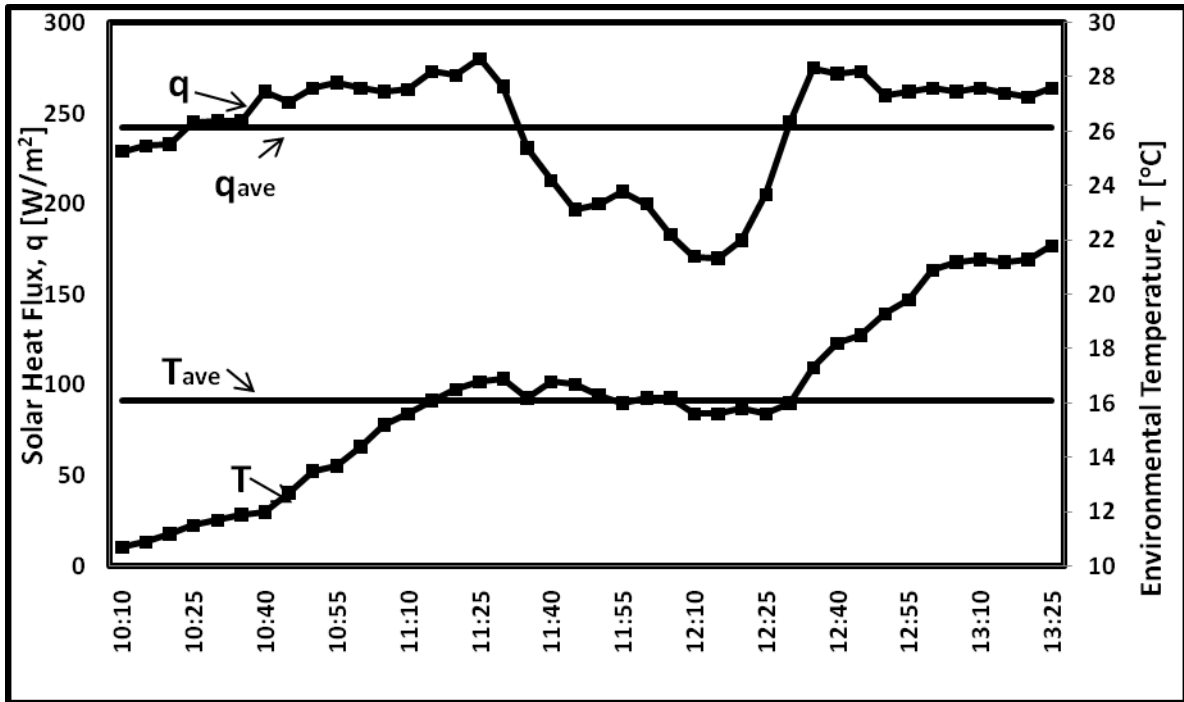


Figure 4 Variation of environmental temperature and solar heat flux during the experiments.

15% of the energy required for office room was provided from solar energy in February 2007. Zhai, et. Al., (2007) claim that 4470 MJ/m^2 solar energy for the hot water supply for the 460 m^2 building area. In our study about 0.96 kW energy is provided by solar energy for the office of 23.31 m^2 . Badran (2004) as shown that solar collector system requires less operation and maintenance work. Our under floor heating system also requires less operation and maintenance work. Sattari

and Farhanieh (2006) as shown that the type and thickness of the floor cover is important parameters in the design of floor heating system. In our experimental study we have also observed that thickness of the floor cover is quite important.

Consequently at Ankara conditions it is not possible to provide thermal comfort conditions with thick clothing ensemble using solar energy or it is possible by

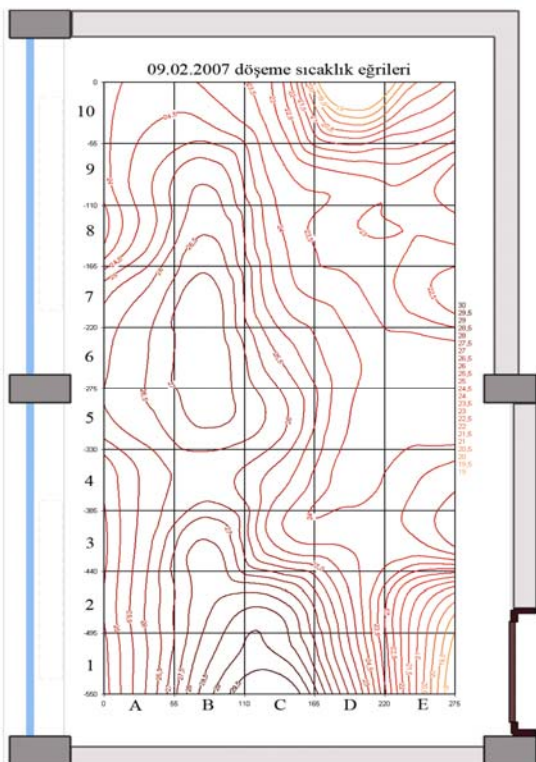


Figure 5. The iso-temperatures of the floor.

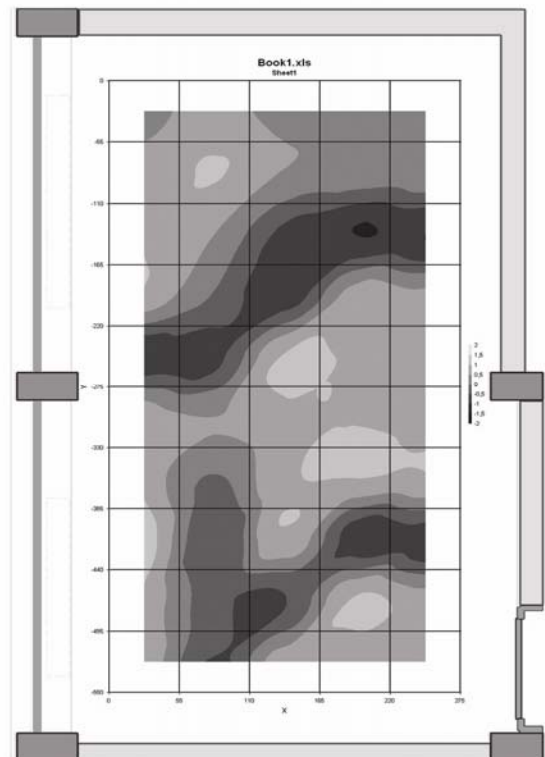


Figure 6. Iso-PMV lines for thick clo-values at 0.20m.

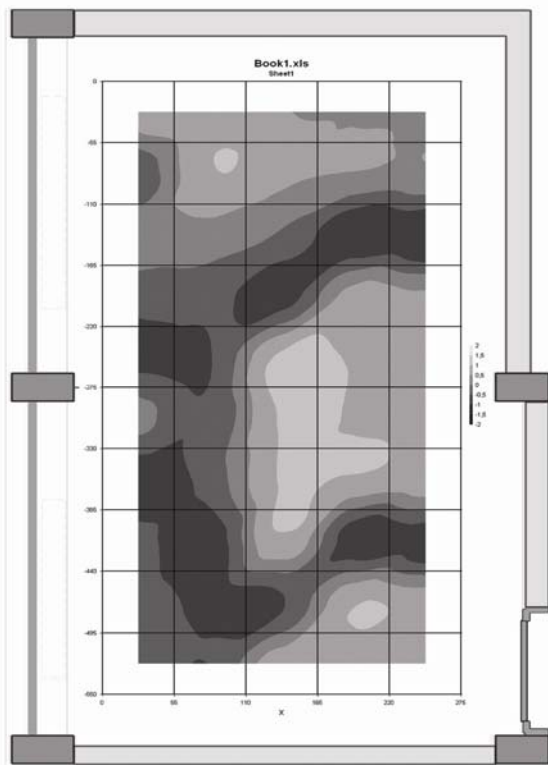


Figure 7. Iso-PMV lines for thick clo-values at 0.60m.

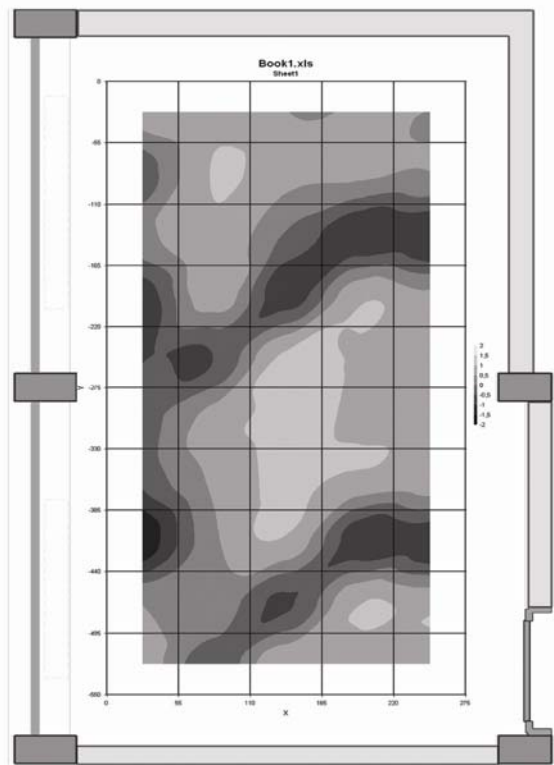


Figure 8. Iso-PMV lines for thick clo-values at 1.00m.

increasing supplementary heat sources. This method of analysis of the thermal comfort is applicable for different type of space heating and cooling systems. On the other hand, if the occupied zone is divided into smaller zones better results could be obtained.

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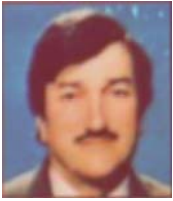
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Cüneyt KURTAY, He was born in Ankara, 1957. He graduated as architect from ADMMA on 1980. He has M.S degree from METU (ODTÜ)-Faculty of Architecture on 1985 and Ph. D. From GAZİ University- Department of Architecture on 1994. He had been Nottingham University, Faculty of Architecture, Nottingham, England, 1996 as Postgraduate student. He is working as Assistant Prof. At Gazi University, department of Architecture. He has research about solar energy, application on renewable energy and lighting in buildings. He has several article and project in Turkey and abroad.



İbrahim ATILGAN, He was born in Eskişehir, 1953. He graduated as Mechanical Engineering from ADMMA on 1979. He has M.S degree and Ph. D. from GAZİ University, department of Mechanical Engineering on 1987 and 1994. He is working as Assistant Prof. At GAZİ University, department of Architecture. He has research about heat transfer, thermodynamic, application on renewable energy and combustion technology. He has several article and project in Turkey and abroad.



Ö.Ercan ATAER, He was born in Ankara, 1949. He graduated as Mechanical Engineering from METU (ODTÜ) on 1970. He has M.S degree and Ph. D. From Lancaster University, UK, Department of Mechanical Engineering on 1974 and 1977. He is working as Prof. at Gazi University, department of Architecture. He has research about heat transfer, thermodynamic and cooling systems. He has several article and project in Turkey and abroad.