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ScienceDirect
Building and Environment 43 (2008) 508–517
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

An approach for energy conscious renovation of residential buildings in Istanbul by Trombe wall system

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Received 23 September 2005; accepted 30 November 2006

Abstract

Turkey has a great potential of solar energy, which is the primary source of renewable energy; however, sufficient benefit cannot be obtained from this clean energy source. In Turkey, 36% of the total energy consumed in buildings is used for heating. Due to the lack of regulations in encouraging the solar energy utilization in buildings, the heating energy consumption plays an important role in the energy economy of our country. Therefore, energy conservation methods become necessary. Energy conservation is important for the existing buildings as for the new buildings. In this study, the south facade of a flat in an existing building in Istanbul in Turkey is recommended to be renovated by the application of Trombe wall principle, which is a well-known indirect passive solar gain system. An approach is proposed for this application and the comparison of the existinsg facade with the renovated facades has been made according to thermal performances and hourly variations of wall interior temperatures. The results of this theoretical application study are given in this paper.

Keywords: Trombe wall; Energy conscious renovation; Solar heating; Heat transfer

1. Introduction

Parallel to the population growth in the world, the energy demands increase and countries search for new methods of energy conservation. Moreover, the consumption of energy, which is mostly of fossil origin, causes environmental problems and troubles in ecological cycles.

Due to the need for supplying the climatic comfort conditions in buildings, most of the energy is used for heating, cooling and climatization of buildings. The most important portion of this energy is consumed for heating in Turkey; therefore, the heating loads should be minimized for the energy economy and reduction of air pollution considering the number of the existing buildings in Turkey, energy economy should also be taken into account for these buildings with energy efficient renovation methods. One of these methods is wall renovation with Trombe wall system, which is covering the black painted south wall of an existing building with a transparent material leaving an inter-space in between. Mostly, the transparent material is glass. The solar radiation on the wall is stored inside the wall as thermal energy and the glass block the transfer of this energy to the environment, since the glass material is permeable to solar rays but impermeable to long-wave thermal radiation. Most of the stored energy is conducted to the inner surface of the wall and then it is convected to the indoor air. In this system, the Trombe wall is massive, and therefore, the temperature variations inside the building caused by the energy stored in the wall during the day are stable and passive heating can be done also during the nighttime through the warmer massive wall.

In this study, solar energy, which is the primary renewable energy source, was used in buildings for passive heating by the combination of unvented Trombe walls with direct gain windows for the retrofit of an existing building. Thermal performances of the existing and the renovated buildings were compared under unsteady-state heat transfer conditions.

All of the calculations were done with computer programs improved and revised for this purpose [1]. The inner surface temperatures were drawn for the designated inside and outside room conditions for 24 h, the heat losses

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0360-1323/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.buildenv.2006.11.033

and gains were calculated depending upon these conditions and the climatic comfort analysis was done.

2. The methodology to compare the thermal performance of the existing and the renovated buildings

The proposed methodology has been developed to determine the change in the thermal performance of the south facade of the living room of the existing building in Istanbul in case it was renovated with Trombe wall system. The method is based on the calculation and comparison of the inner surface temperatures and heat losses through the existing and renovated envelopes. The heat transfer calculations were solved for these calculations under unsteady-state conditions by using finite difference method. In this study, for energy efficient renovation of the building, it was recommended to cover the exterior side of the wall with glass with three different inter-space distances, which are 0.05, 0.10 and 0.15 m. At the same time, different materials for the opaque construction of the envelope were proposed and it was assumed that the same type of glass cover was used for these envelope alternatives. In order to evaluate the thermal performances, the calculations of the inner surface temperatures and heat flow amount through the existing and recommended–renovated walls were done. This proposed renovation method was theoretically applied to a residential building in Istanbul. The location of the sample building is shown in the site plan in Fig. 1.

The method was applied to the south-facing living room of the selected apartment in the sample building. The selected apartment was located on the middle floor of the building. As it is seen from the site plan the envelope of the selected apartment was not shaded by other buildings. The plan of the selected apartment and the living room in this apartment is shown in Fig. 2. The details of the floor and the partitions are shown in Table 1.

The window of the existing wall was wooden-framed with 6-9-6 double glass having a heat transfer coefficient of $1.66\,\mathrm{W/m^2\,^\circ K}$. The transparency ratio of the room is 23%. For an existing building, it is difficult to make changes in the other design parameters; that is why, for the energy efficient renovation of this existing envelope, glass cover on the exterior side was recommended. The heat transfer coefficient of the glass cover is $U_s = 1.90\,\mathrm{W/m^2\,^\circ K}$.

The details of the existing wall, recommended wall alternatives with different materials and the renovation of them with glass covers are given in Tables 2 and 3, respectively. The renovated envelope details were formed with inter-space distances of 0.05, 0.10, and 0.15 m. The absorption coefficient of the solar radiation for the existing façade, which was light coloured, was taken as 0.4 and for the renovated walls behind the glass which were dark coloured was taken as 0.7. The section of the renovated wall detail is seen in Fig. 3.

The building is used the whole day and should be heated 24 h. Thus, the operating period and indoor air temperatures for additional mechanical heating system were assumed as follows: between 08:00 and 24:00; t_i : 19 °C.

3. The calculation of the inner surface temperatures and the heating energy demand for the existing envelope

Since the inner surface temperatures of the partitions surrounding a room are equal to the indoor air temperature of a room, the inner surface temperatures of the transparent and the opaque components of the building envelope are the main determinants of the indoor thermal conditions. Therefore, the thermal performance of a room should be evaluated according to the surface temperatures of the envelope besides indoor air temperatures; since the surface temperatures are as important as indoor air temperature on thermal comfort.

Since the heat storage capacity of the opaque materials cannot be neglected, the time dependent heat flow through the opaque component can be calculated by finite difference method which is a well-known solution to unsteady-state heat transfer equations.

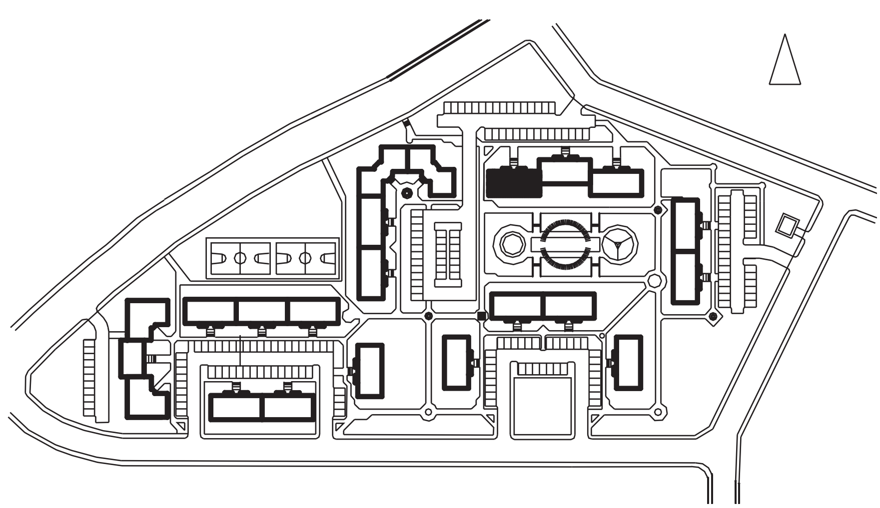


Fig. 1. The site plan where the sample building is located.

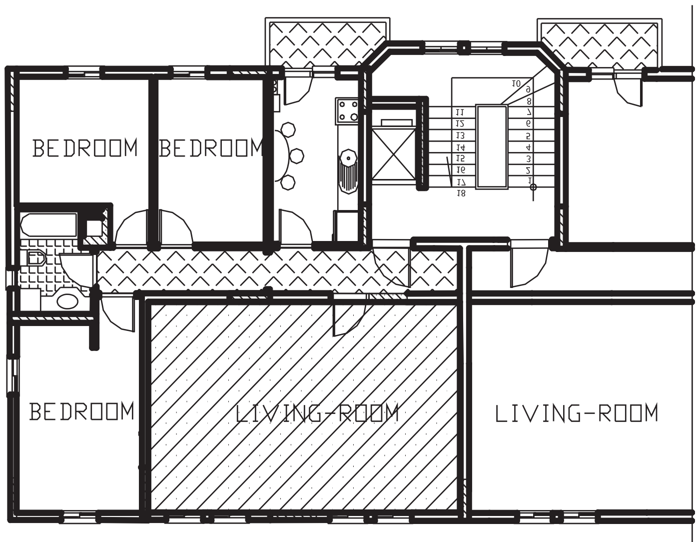
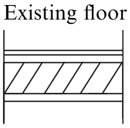
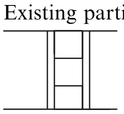


Fig. 2. The plan of the selected apartment and the living room in this apartment.

Table 1
The details of the existing floor, the partitions and the envelop

The details of the existing floor and the partitions	Layer number	Material name	Thickness (m)	Thermal conductivity λ(W/m °K)	Heat transfer coefficient U(W/m^2 °K)
Existing floor 	1	Carpet	0.015	0.24	2.40
	2	Alum	0.02	0.35	
	3	Concrete floor	0.1	2.088	
	4	Stucco plaster	0.02	0.35	
Existing partition 	1	Stucco plaster	0.02	0.35	2.12
	2	Vertical perforated brick	0.085	0.52	
	3	Stucco plaster	0.02	0.35	

The time dependent values of the inner surface temperatures and indoor air temperature are calculated by finite difference approach in this study to determine the thermal performance of the existing building envelope [2].

The time dependent temperature variation in the opaque component can be represented by the following formula:

$$\frac{\partial t}{\partial T} = a\frac{\partial^2 t}{(\partial x)^2}. \tag{3.1}$$

The numerical solution of Eq. (3.1) with finite difference method obtains temperatures for 'n' point at $(T + \Delta t)$ period as follows:

$$\frac{t_{n+1} + t_{n-1} - 2t_n}{(\Delta x)^2} = \frac{1}{a}\frac{t_n^* - t_n}{\Delta T}, \tag{3.2}$$

where t_n, t_{n+1}, t_{n-1} are the temperatures of the layers with Δx thickness (°C), t_n' is the temperature in 'n' layer at $(T + \Delta t)$ time (°C), a the thermal emissivity (m^2/s), $a = \lambda/\rho c$, ρ the specific weight (kg/m^3) and c the specific heat [J/kg °C].

The temperature of a point n in the component at a certain time (°C) is as follows:

$$t_n^* = \frac{a\Delta T}{(\Delta x)^2}(t_{n+1} + t_{n-1}) + \left(1 - \frac{2a\Delta T}{(\Delta x)^2}\right)t_n, \tag{3.3}$$

where Δx is the distance difference in the component along x direction (m).

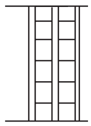
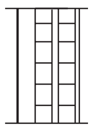
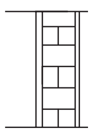
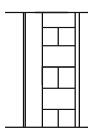
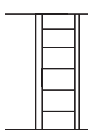
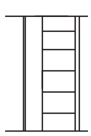
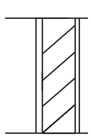
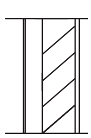
During the solving of this equation, the ΔT time and Δx dimension should be taken providing the condition below:

$$\frac{(\Delta x)^2}{a\Delta T} \geqslant 2. \tag{3.4}$$

If the finite difference method is used for the calculations of the opaque component, the inner surface temperature of the wall can be calculated with the equation below:

$$t'_{\mathrm{wi}} = \frac{a_1 \cdot \Delta T}{(\Delta x)^2}\left(2\frac{\Delta x}{\lambda_1}b \cdot S_i + 2\frac{\alpha_i \cdot \Delta x}{\lambda}t_i + 2t_2 + t_1\left(\frac{(\Delta x)^2}{a\Delta T} - \frac{2\Delta x\alpha_i}{\lambda} - 2\right)\right), \tag{3.5}$$

Table 2
The details of the existing wall, recommended wall alternatives and the renovation of them with glass cover

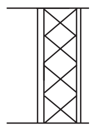
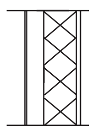
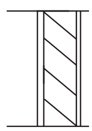
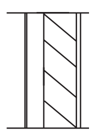
Alternative no	Wall detail	Layer number	Material name	Thickness (m)	Thermal conductivity λ (W/m °K)
A.0.		1	Limed plaster	0.030	0.870
		2	Vertical perforated brick	0.085	0.520
		3	Polystyrene	0.030	0.040
		4	Vertical perforated brick	0.085	0.520
		5	Stucco plaster	0.020	0.350
A.0.1.		1	Glass (6-9-6)	0.006	0.800
A.0.2.		2	Iter-space	0.050	0.024
A.0.3				0.100	
				0.150	
		3	Vertical perforated brick	0.085	0.520
		4	Polystyrene	0.030	0.040
		5	Vertical perforated brick	0.085	0.520
		6	Stucco plaster	0.020	0.350
A.1.		1	Limed plaster	0.030	0.870
		2	Solid brick	0.200	0.790
		3	Stucco plaster	0.020	0.350
A.1.1.		1	Glass (6-9-6)	0.006	0.800
A.1.2.		2	Inter-space	0.050	0.024
A.1.3.				0.100	
				0.150	
		3	Solid brick	0.200	0.790
		4	Stucco plaster	0.020	0.350
A.2.		1	Limed plaster	0.030	0.870
		2	Vertical perforated brick	0.200	0.520
		3	Stucco plaster	0.020	0.350
A.2.1.		1	Glass (6-9-6)	0.006	0.800
A.2.2.		2	Inter-space	0.050	0.024
A.2.3.				0.100	
				0.150	
		3	Vertical perforated brick	0.200	0.520
		4	Stucco plaster	0.020	0.350
A.3.		1	Limed plaster	0.030	0.870
		2	Perforated concrete block	0.200	0.640
		3	Stucco plaster	0.020	0.350
A.3.1.		1	Glass (6-9-6)	0.006	0.800
A.3.2.		2	Inter-space	0.050	0.024
A.3.3.				0.100	
				0.150	
		3	Perforated concrete block	0.200	0.640

where t_{wi} is the opaque component's inner surface temperature at $(T+\Delta T)$ time (°C), a_1 the thermal emissivity of inner surface material (m/s), λ_1 the thermal conductivity of inner surface material (W/m °K), b the opaque component's inner surface solar radiation absorption coefficient, S_i the solar radiation intensity on the inner surface which is transmitted by the transparent component (W/m^2), α_i the component inner surface convection coefficient (W/m^2 °C), t_i the indoor air temperature (°C), t_2 the temperature of layer which is Δx away from inner surface at (T) time (°C) and t_{wi} the opaque component inner surface temperature at (T) time (°C).

For surface temperature calculations, ΔT and Δx should be selected to provide the following condition:

$$\frac{(\Delta x)^2}{a\,\Delta T} \geqslant 2\left(\frac{\alpha\,\Delta x}{\lambda}+1\right). \tag{3.6}$$

Table 3
The details of the recommended wall alternatives and the renovation of them with glass cover

Alternative no	Wall detail	Layer number	Material name	Thickness (m)	Thermal conductivity λ (W/m °K)
A.4.		1	Limed plaster	0.030	0.870
		2	Gas concrete 1	0.200	0.350
		3	Stucco plaster	0.020	0.350
A.4.1.		1	Glass (6-9-6)	0.006	0.800
A.4.2.		2	Inter-space	0.050	0.024
A.4.3.				0.100	
				0.150	
		3	Gas concrete 1	0.200	0.350
		4	Stucco plaster	0.020	0.350
A.5.		1	Limed plaster	0.030	0.870
		2	Gas concrete 2	0.200	0.190
		3	Stucco plaster	0.020	0.350
A.5.1.		1	Glass (6-9-6)	0.006	0.800
A.5.2.		2	Inter-space	0.050	0.024
A.5.3.				0.100	
				0.150	
		3	Gas concrete 2	0.200	0.190
		4	Stucco plaster	0.020	0.350

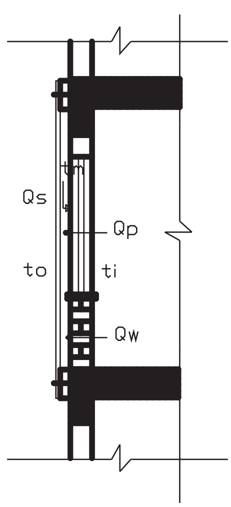


Fig. 3. The section of the renovated wall detail.

As the heat storage capacity of transparent materials is negligable, the calculations for heat flux can be done under steady-state conditions. Thus, the inner surface temperature of the transparent component was calculated with the equation below:

$$t_{P2} = \frac{(U_P(t_{ep} - t_i) - (F_P \cdot I_r \cdot d_r + I_r \cdot d_r) + \alpha_i \cdot t_i)}{\alpha_i}, \quad (3.7)$$

where t_{P2} is the inner surface temperature of inner skin's glass at certain time (°C), d_R the glass's direct solar radiation transmittance, d_r the glass's diffuse solar radiation transmittance, F_P the proportion of glass's shaded area to whole glass area and U_P the overall heat transfer coefficient of transparent component (W/m^2 °C).

Indoor air temperature can be calculated according to the heat gains and losses of the room at a certain time with the equation below:

$$t_i' = t_i + \frac{\Delta T}{m \cdot c_p}\left(\sum_1^n A_o \cdot \alpha_i(t_{wi} - t_i) + \sum_1^m A_p \cdot \alpha_i(t_{p2} - t_i) + b_h \sum_1^m (I \cdot A_p) + Q_{in} + Q_h\right), \quad (3.8)$$

where t_i' is the indoor air temperature at certain $(T + \Delta T)$ time (°C), t_i the indoor air temperature at T time (°C) and m the mass of air in the building (kg).

The terms in the parenthesis express air's heat loss and heat gain at ΔT time.

- $\sum_1^n A_o \cdot \alpha_i \cdot (t_{wi} - t_i)$ heat flux between 'n' unit opaque component surface and air at ΔT time
- $\sum_1^m A_p \cdot \alpha_i(t_{p2} - t_i)$ heat flux between 'm' unit transparent component surface and air at ΔT time (W).
- b_h absorption coefficient of air's solar radiation, which is through transparent components
- $\sum_1^m (I \cdot A_p)$ solar radiation intensity through 'n' unit transparent component (W)
- Q_{in} heat flux by infiltration at ΔT time (W)
- Q_h heat gain from heat sources in the room at ΔT time (W)

4. The calculation of the inner surface temperatures and the heating energy demand for the renovated envelope with Trombe wall system

In existing buildings, due to the difficulty in changing the other parameters and their relation to other factors, the retrofit should be done to the building envelope to decrease the heating energy costs. In this study, an approach is proposed for the renovation of the existing building by the application of Trombe wall principle (indirect solar gain system) to the opaque component of the building envelope.

The calculation method, which is used for thermal performance evaluation of the renovated wall, has two steps:

In the first step, a method proposed by B. Todorovic for the calculation of hourly inter-space temperatures of double-skin facades is revised and some additions that are lacking in his method are done [3].

In the second step, the hourly inter-space temperatures calculated in the first step, are taken as the hourly outdoor air temperatures. The inner surface wall temperatures are calculated according to the finite difference numerical approach for the time dependent heat transfer equations.

In winter, the ventilation doors are kept closed so as to not lose the heat which is gained during day time. In summer, the inter-space should be ventilated to prevent overheating. As the design day chosen for this study is the specific day for heating period, the envelope is assumed to be unvented during this period and the thermal performance of the existing and the renovated walls is evaluated from heating energy point of view.

The method of B. Todorovic aims to analyse the effect of double-skin facade buildings to the heating and cooling loads by the calculation of the inter-space temperatures. This method is used in renovating the facade of an existing building with Trombe wall system with a little modification for taking the effects of direct and diffuse solar radiation separately.

According to the heat balance equations for the external envelope, the hourly inner surface temperatures of the external envelope (t_s) are calculated. As the internal envelope is composed of opaque and transparent components having different heat storage capacities, heat balance equations are written separately. The hourly inner surface temperatures of the transparent component (t_p) are obtained from these equations. Then, the heat balance equation for the opaque component is written under unsteady-state conditions. After that, the hourly inner surface temperatures of the opaque component facing the inter-space (t_w) are calculated [3]. After calculating the surface temperature of the wall facing the inter-space and the surface temperature of the exterior envelope facing the inter-space, the heat balance equations are written for inter-space's heat losses and gains. The inter-space heat balance is

$$Q_v = Q_s + Q_p + Q_w, \tag{4.1}$$

where Q_v is the absorbed heat in the inter-space, Q_s the heat flow from exterior envelope to inter-space by convection, Q_p the heat flow from window surface to inter-space and Q_w the heat flow from wall's outer surface to inter-space temperature. If t_m is solved from the equation above:

$$t_m = \frac{F_s \cdot D \cdot c_p \, \rho \, t'_m + F_s \, \alpha_{s2} \, t_s + F_p \, \alpha_{p1} \, t_p + F_w \, \alpha_{w1} \, t_w}{F_s \cdot D \cdot c_p \, \rho + F_s \, \alpha_{s2} + F_p \, \alpha_{p1} + F_w \, \alpha_{w1}}, \tag{4.2}$$

where F_S is the outer skin area (m^2), F_P the window area in inner skin (m^2), F_W the wall area (m^2), D the distance between two skin (m), t_p the window's outer surface temperature (°C), t_W the wall's outer surface temperature (°C), t'_m the inter-space temperature in previous period (°C), t_m the inter-space temperature (°C), c_p the specific heat of air $c_p = 1005\,\mathrm{J/kg\,°C}$, t_s the outer skin inner surface temperature (°C), α_{w1} the wall outer surface coefficient of heat transfer by convection (W/m^2 °C), α_{p1} the window outer surface coefficient of heat transfer by convection (W/m^2 °C) and (α_{s2}) the outer skin outer surface coefficient of heat transfer by convection (W/m^2 °C).

The inter-space temperatures which are calculated with Eq. (4.2) are accepted to be the outside air temperatures and the heat transfer calculations through the inner envelope are done according to the method explained in Section 3 for heat transfer through the opaque and transparent parts of the inner envelope.

5. Thermal evaluation of the existing and energy conscious renovated walls

The thermal performances of the existing and the renovated walls of the living room in the sample building have been evaluated according to the calculated inner surface temperatures and heat flow amount through the envelope [4]. The hourly variations of indoor air temperatures, inner surface temperatures and the heat losses and gains are seen in Figs. 4–14.

The hourly indoor air temperature variations for the existing wall and its renovated forms with glass cover with 0.05, 0.10 and 0.15 m of inter-space distances and the proposed wall alternatives renovated with the same inter-space distances are seen in Figs. 4–6. As explained above, for the calculations it has been assumed that the heating system is operating to keep the indoor air temperature at 19 °C between 08:00 and 24:00.

The indoor air temperature for the existing wall was 15.2 °C at 24:00 and it drops down up to 9.39 °C until 07:00. The outdoor air temperature is less than the indoor air temperature between the hours 24:00 and 07:00; that is why, the heat loss occurs from inside to outside. The indoor air temperature increases to 19 °C at 08:00 by means of the mechanical heating system; and then, it is kept at 19 °C till 24:00. The indoor air temperature drops to its floating value without mechanical heating system. For the

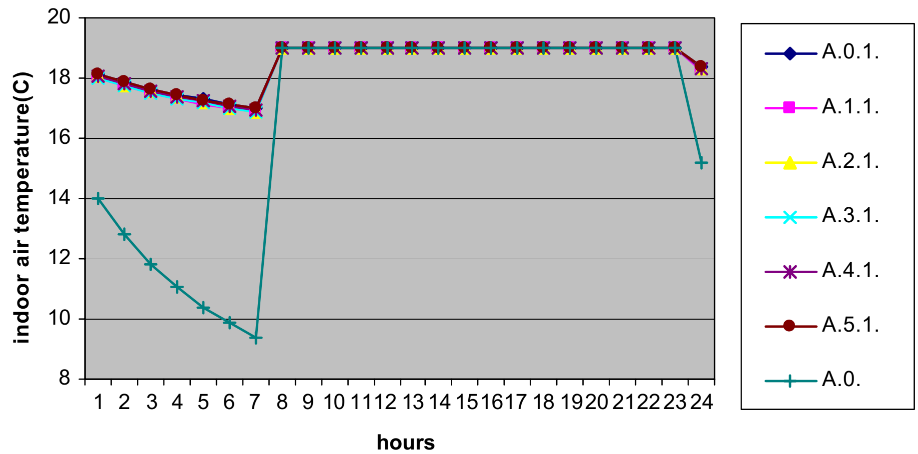


Fig. 4. The indoor air temperature variations of the existing wall and the proposed wall alternatives with glass cover of 5 cm of inter-space distance.

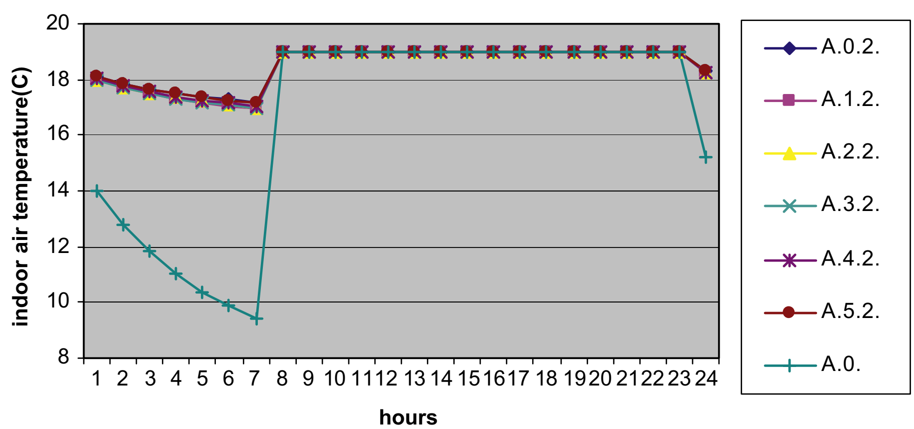


Fig. 5. The indoor air temperature variations of the existing wall and the proposed wall alternatives of their renovated versions with glass cover of 10 cm of inter-space distance.

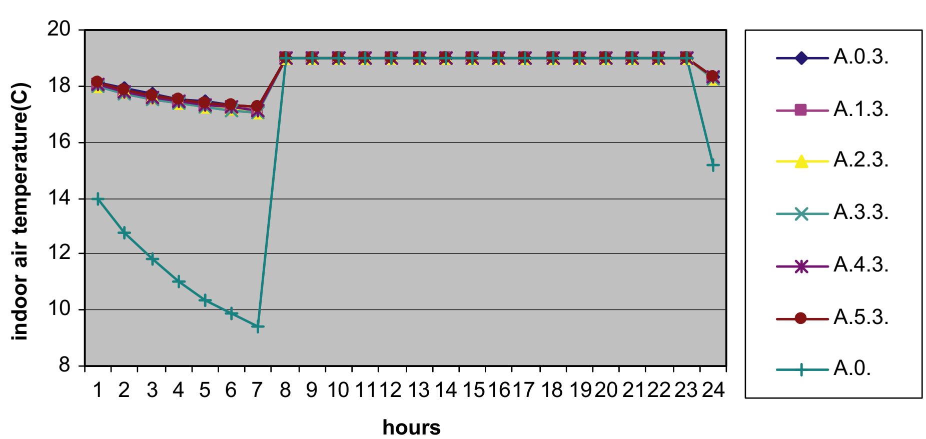


Fig. 6. The indoor air temperature variations of the existing wall and the proposed wall alternatives of their renovated versions with glass cover of 15 cm of inter-space distance.

renovated samples with Trombe wall system, the inside air temperature drops from 19.43 °C at 24:00 to 18.07 °C at 07:00. That means that the heat loss of the renovated walls is significantly less than the existing one. The hourly inner surface temperatures of the existing and the renovated walls are given in Figs. 7–9. As seen from the figures, the inner surface temperature for the renovated sample increases from 18.07 °C to 18.97 °C at 08:00 and it reaches

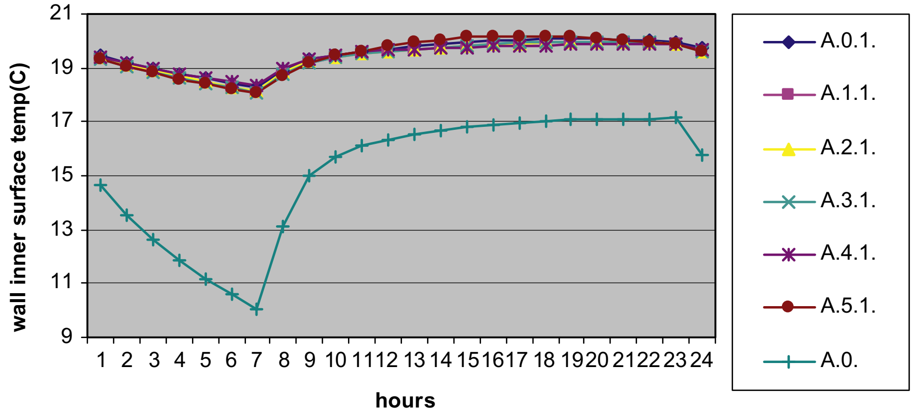


Fig. 7. The wall inner surface temperature variations of the existing wall and the proposed wall alternatives of their renovated versions with glass cover of 5 cm of inter-space distance.

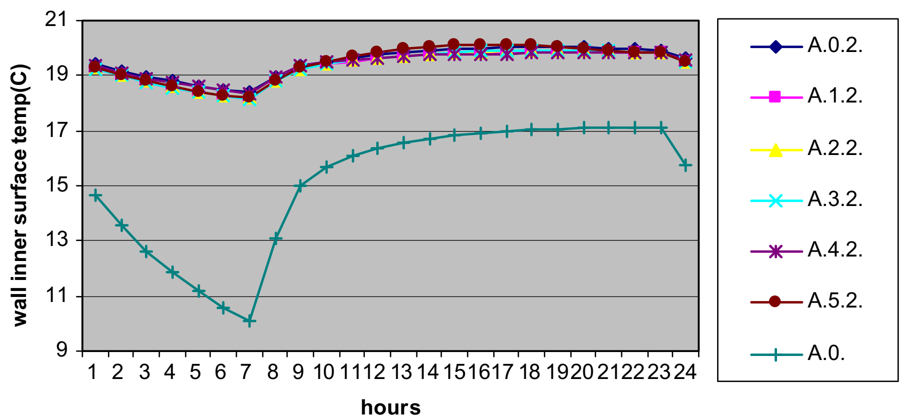


Fig. 8. The wall inner surface temperature variations of the existing wall and the proposed wall alternatives of their renovated versions with glass cover of 10 cm of inter-space distance.

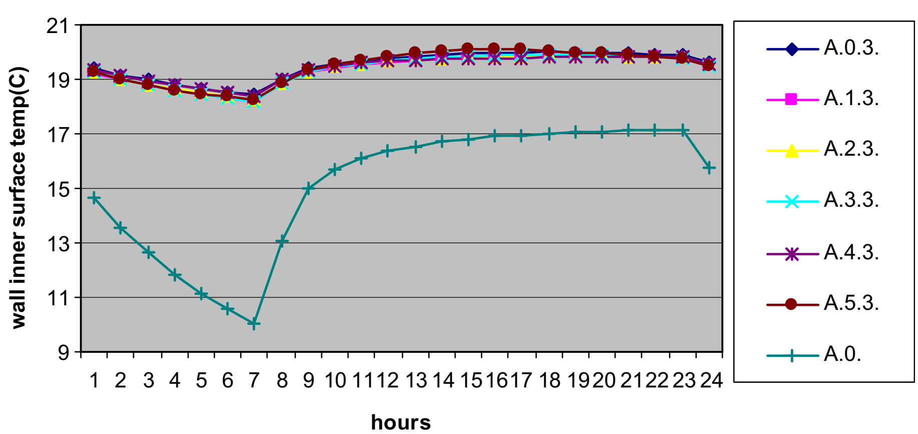


Fig. 9. The wall inner surface temperature variations of the existing wall and the proposed wall alternatives of their renovated versions with glass cover of 15 cm of inter-space distance.

up to 20.19 °C till 24:00. A sudden decrease is seen afterwards, due to the decrease in indoor air temperature.

The hourly wall inner surface temperatures of the existing and the proposed wall alternatives without a glass cover are given in Fig. 10 As seen in the figure, the renovated walls without a glass do not affect the amount of energy conserved much but the renovated walls with Trombe wall system have dramatic effects on the energy conserved.

The heat gains and losses of the existing and proposed walls with glass cover are seen in Figs. 11–13. As seen in the

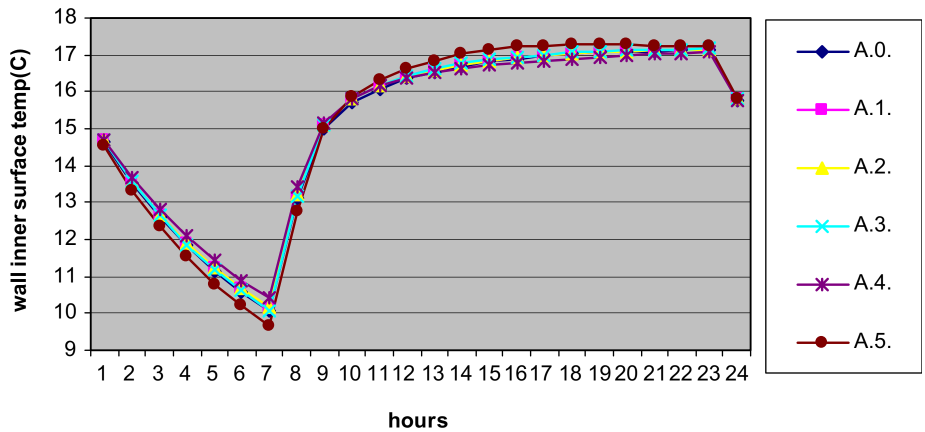


Fig. 10. The wall inner surface temperature variations of the existing wall and the proposed wall alternatives without renovation with glass cover.

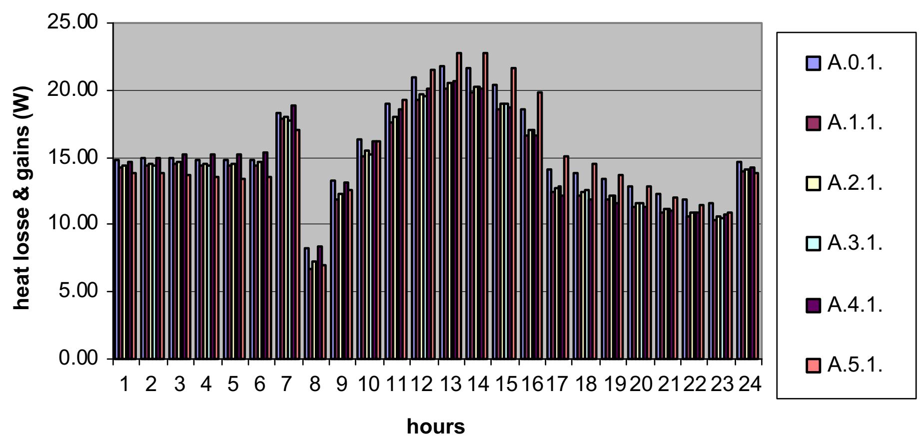


Fig. 11. The heat gains and losses of the existing wall and the proposed wall alternatives renovated with glass cover of 5 cm of inter-space distance.

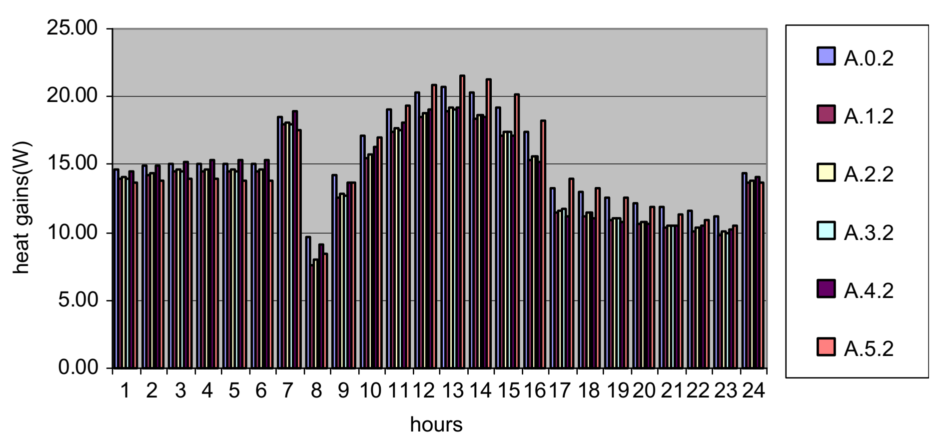


Fig. 12. The heat gains and losses of the existing wall and the proposed wall alternatives renovated with glass cover of 10 cm of inter-space distance.

figures, the change in the inter-space distance does not affect the heat flow amount much. The heat gains and losses of the existing and the proposed walls without a glass cover are given in Fig. 14. As seen, the heat loss occurred in these samples and the renovation of the wall with glass cover causes a significant effect in the heat gains through the external wall.

6. Conclusions

It is getting to be more difficult and more expensive for energy to be found and the environmental pollution is getting worse; that is why, the scientists are trying to lessen the energy consumption in buildings via the application of new renovation methods to building, besides the instructions for new

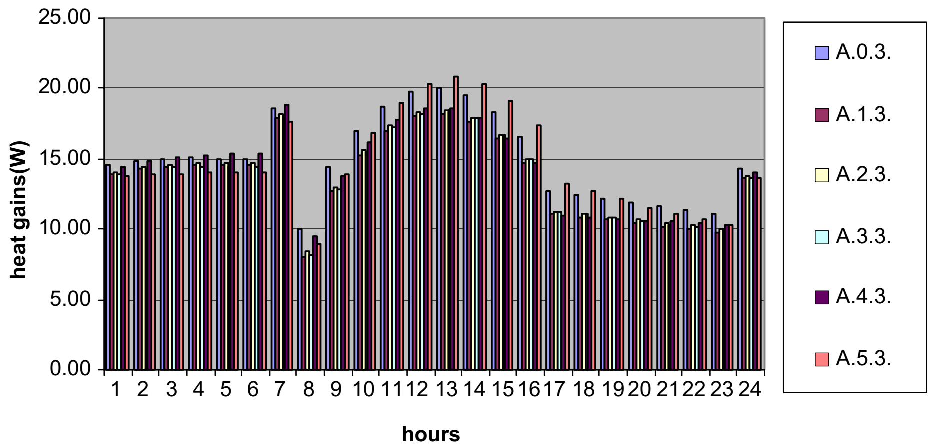


Fig. 13. The heat gains and losses of the existing wall and the proposed wall alternatives renovated with glass cover of 15 cm of inter-space distance.

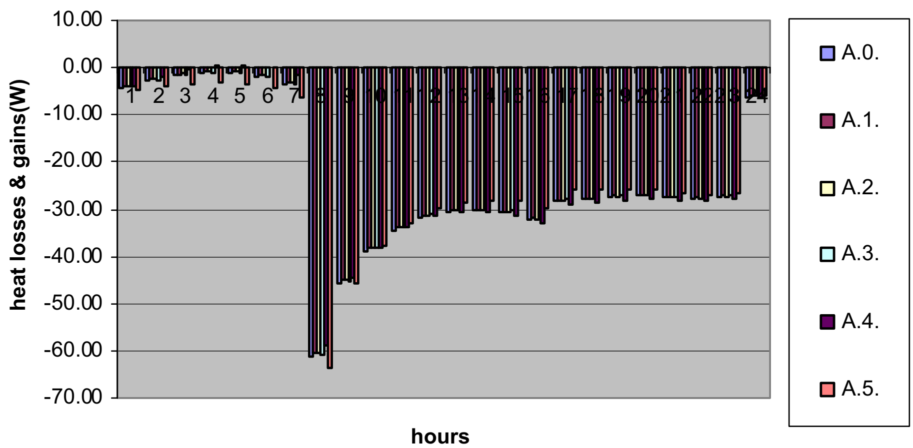


Fig. 14. The heat gains and losses of the existing wall and the proposed wall alternatives without glass cover.

building design considering the large amount of energy that is consumed for heating and cooling of buildings.

In this study, a new approach for the renovation of the building facades with Trombe wall system is developed, applied theoretically to the south faced external wall of the existing building in Istanbul. Different wall materials are also proposed besides glass cover. Then, the existing, recommended and renovated facades for a designated design day of the winter period are compared from their thermal performance point of view.

The results show that changing the main material of the envelope does not affect the inside air and inner surface temperatures much while renovating the envelope with Trombe wall system affects the system performance a lot. The inter-space distance is not significantly effective on the system performance, either. The application of the system even to the facade of a sample room has a significant amount of energy conservation and changing the wall material is not very effective. Therefore, the renovation of an existing building with the recommended passive system will bring a great amount of energy economy to Turkey. If the proposed system was applied to the whole facade of a building and the calculations were done for the whole heating period rather than a chosen design day, the importance of the decrease in the amount of energy consumption in buildings would more easily be seen.

Using the sustainable energy sources in buildings will help lessen the use of fossil fuels and their damage to the ecological cycles.

In this study, only the winter heating is observed. The cooling loads for the summer should also be calculated. For summer, it will be assumed that outer glass cover will have ventilation openings to avoid excess heat gain from solar radiation. As a result, the results gained parallel to the findings cannot be applied to every climatic region. So, studies should be done for every climatic region separately.

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