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Numerical evaluation of solar-energy use through passive heating of weekend houses in Yugoslavia

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Abstract

Use of solar energy through passive heating is numerically evaluated for different passive designs of weekend houses with one wall made completely of masonry and with other walls made of two layers: a masonry layer and a thermal-insulation layer. To access this problem, the heating and cooling load is determined by using a dynamic, thermal, building model newly constructed on the basis of finite volumes and time marching. The investigation is performed for two days: one winter day for the weekend house with the masonry wall facing south, and for one summer day for the weekend house with the masonry wall facing north. The heating and cooling loads are evaluated for different thicknesses of masonry by using two investigation procedures where in the first procedure the insulation thickness is kept constant, and in the second procedure the *U* value of the two-layer walls of the house is kept constant. When the thermal-insulation layer faces the outside of the house, this investigation reveals that the use of the passive house instead of the non-passive house for the winter day gives an energy saving of around 1.5%, and for the summer day gives the maximum energy saving of around 4% for a masonry thickness of 30 cm. When the thermal-insulation layer faces the inside of the house, the investigation reveals that passive heating is not possible at all. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

High consumption of energy in buildings and high pollution of the Earth that comes with this energy production motivate research institutions around the globe to construct different software tools to investigate how to decrease energy consumption in houses while maintaining good thermal comfort. To accomplish this, a passive house design that uses solar energy to decrease heating and cooling loads of a house [1–3] is investigated.

With increasing power and the low price of personal computers, proliferation of building energy software tools has increased; 215 such tools were found among International Energy Agency countries in 1995 [4]. These tools use: (1) energy parameters [5]; (2) physical laws [1,3,6–8]; and (3) performance data [9–11] to predict building energy performance. The physical models use three basic methods [6]: numeric [1]; harmonic [7]; and response [3,8]. These thermal building models are used for the calculation of different types of buildings: single and multiple zones; thermally light and heavy; low and high rise [5]; and residential and office buildings [5,12]. Also the building models integrate models of HVAC systems [7,10], of airflow in buildings [13], and of passive solar, photovoltaic and combined power and heating systems [14]. These models use either simulation or sensitivity analysis to design and retrofit a building, and evaluate its heating and cooling performance [2,12,15]. These models can be either cheap to use such as the one zone model of BRE-ADMIT [16], or costly and time consuming, such as DOE-2 [15,17,18], BLAST [19], TRNSYS [20], BUNYIP [21], and ESP [14].

Our thermal, building software tool ZID uses physical laws to calculate thermally heavy, single-zone buildings numerically. This dynamic building model is used for building design and retrofit. The model is based on the finite volume and time marching techniques. This model takes into account time variations of outside temperature and solar irradiance. The model is validated by comparing its results with experimental results and the results of a satellite version of BRE-ADMIT software [16].

Numerical investigations described in this paper expand the up-to-date knowledge in the use of solar energy by an evaluation of the influence of passive design of weekend houses in Yugoslavia on their loads for heating and cooling. The weekend house with the passive design has one wall made completely of one-layer masonry, and other walls made of two-layers: a masonry layer and a thermal-insulation layer where the thermal-insulation layer may either face inside or outside the house. At weekends at the beginning of its use, this house will have temperatures that are approximately equal to that of the outside air. The investigation of weekend houses is performed for two days: one winter day for a weekend house with the one-layer wall facing south, and for one summer day for a weekend house with the one-layer wall facing north. This investigation uses two procedures where in the first procedure the thermal-insulation thickness is kept constant, and in the second procedure the U-value of the two-layer walls is kept constant. This investigation reveals the values of loads for heating and cooling of different weekend houses when the thickness of their masonry layer is varied.

These loads are not equal to the energy consumption for heating and cooling, and when this energy consumption should be evaluated, the coefficients of performance of heaters and coolers should be considered.

The remainder of the paper is in four sections. The first section describes the mathematical model of a house. The second section describes the experimental validation. The third section describes the simulation, and the fourth section describes the results and discussion.

2. Mathematical model of a house

A mathematical model is developed for the house shown in Fig. 1. The house consists of one zone and has a one-slope roof. The house has an envelope with six surfaces: north wall (j = 1), west wall (j = 2), south wall (j = 3), east wall (j = 4), roof (j = 5) and floor (j = 6). An envelope structure of the house is presented in Fig. 2 where the envelope structure j is shown with its layers, temperatures, and heat transferred between layers. The layers i−1, i, i + 1 stand inside the structure,

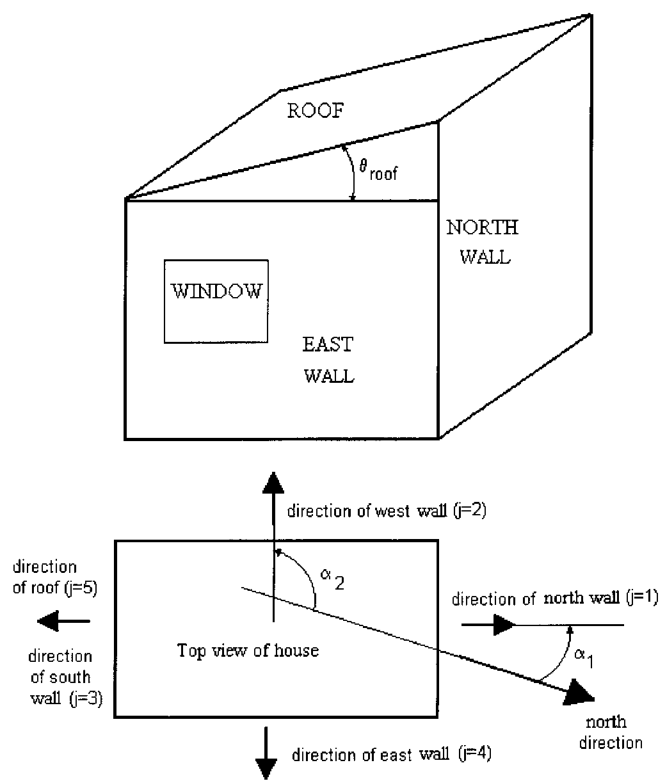

Fig. 1. Schematic of the building.

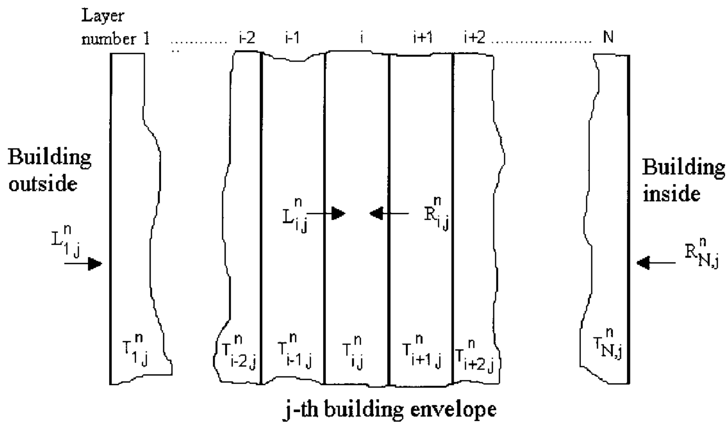

Fig. 2. The structure of j-th building envelope.

layer i = 1 faces the outside of the house, and layer i = N faces the inside of the house. The heat $L^n_{i,j}$ is transferred from the layer i−1 to the layer i, heat $R^n_{i,j}$ is transferred from the layer i + 1 to the layer i, the heat $L^n_{1,j}$ is transferred from the outside to the layer i = 1 and heat $R^n_{Nj,j}$ is transferred from the inside to the layer i = N, where n refers to time.

The mathematical model is used to calculate:

1. Heat transfer inside an envelope structure.
2. Heat transfer between the building and the outside.
3. Heat transfer inside the building.
4. Load for heating and cooling during a time interval Δt.
5. Load for heating and cooling during a whole day.

The heat transfer inside the envelope structure is calculated when $L^n_{i,j}$, $R^n_{i,j}$, and the temperature $T^{n+1}_{i,j}$ of the layer i at time (n + 1) are obtained by using equations:

$$L^n_{i,j} = (T^n_{i-1,j} - T^n_{i,j})A_j k_{i,j}/\Delta x_{i,j}, \tag{1}$$

$$R^n_{i,j} = (T^n_{i+1,j} - T^n_{i,j})A_j k_{i,j}/\Delta x_{i,j}, \tag{2}$$

$$T^{n+1}_{i,j} = T^n_{i,j} + (L^n_{i,j} + R^n_{i,j})\Delta t/(c_{i,j}\rho_{i,j}A_j\Delta x_{i,j}). \tag{3}$$

Here, A_j stands for the heat-transfer surface of the structure j (the same for all layers in structure j), $k_{i,j}$ stands for the coefficient of heat conductivity of the layer i, $\rho_{i,j}$ stands for the density of the layer, $c_{i,j}$ stands for the specific heat capacity of the layer and $\Delta x_{i,j}$ stands for the thickness of the layer.

The heat transfer between the house and the outside is calculated by using the equation:

$$L^{n}_{1,j} = A_j h_o[(T^{n}_{ou} + T^{n+1}_{ou})/2 - T^{n}_{1,j}] + A_j \epsilon_j H^{n}_{j}(1 - p_j) + Qr^{n}_{j}. \tag{4}$$

The right-hand side of this equation has three terms. The first term stands for heat transfer by convection from the outside to the structure, the second term stands for heat transfer by solar radiation from the outside to the structure, and the third term stands for the heat transfer by radiation from the structure to the outside. In the first term, h_o stands for the coefficient of convective heat transfer, and T^{n}_{ou}, T^{n+1}_{ou} stand for the outside air temperatures at times n and (n+1), respectively (see Appendix A), and $T^{n}_{1,j}$ stands for the temperature of the layer facing the outside of the structure. It is assumed that $T^{n}_{1,6} = T_g$ for the floor layer in direct contact with the soil where the temperature T_g of the soil has constant value during the day. In the second term, ϵ_j stands for the coefficient of radiation emission, H^{n}_{j} stands for the solar-radiation intensity on surface and p_j stands for the glass-surface part in the structure. The third term is calculated as:

$$Qr^{n}_{j} = 0 \quad \text{for } T^{n}_{ou} > T^{n}_{1,j}, \tag{5}$$

$$Qr^{n}_{j} = 5.67 A_j \epsilon_j[(T^{n}_{ou}/100)^4 - (T^{n}_{1,j}/100)^4] \quad \text{for } T^{n}_{ou} < T^{n}_{1,j}. \tag{6}$$

The heat transfer inside the house is calculated by using the equation

$$Q^{n}_{hc} + Q^{n}_{inf} + \sum_{j=1}^{6}(Q^{n}_{sr,j}) = m_i c_i(T^{n+1}_{in} - T^{n}_{in})/\Delta t + \sum_{j=1}^{6}(R^{n}_{N,j}). \tag{7}$$

The left-hand side of this equation consists of three terms. The first term Q^{n}_{hc} represents the heat flux used for heating or cooling (negative) of the air from thermal comfort temperature T_{tc} to the temperature needed to cover the heat loss or gain from the house interior. The second term

$$Q^{n}_{inf} = c_{inf}\,\ell(T^{n}_{ou} - T^{n}_{in}) \tag{8}$$

presents heat flux used for the heating or cooling (negative) of infiltration air to T_{tc}, where c_{inf} stands for the infiltration coefficient, and ℓ stands for the total length of infiltration gaps in the house structure. The third term

$$Q^{n}_{sr,j} = p_j A_j H^{n}_{j} \tag{9}$$

presents the gain of solar-radiation flux through windows on the wall.

The right-hand side of Eq. (7) consists of the two terms. The first term presents heat accumulated in the house interior where

$$m_{in}c_{in} = \rho_a c_a V_{in} + m_{fu}c_{fu} \tag{10}$$

stands for the total heat capacity of the inside air and furniture, ρ_a stands for the air density, c_a stands for the air specific heat, V_{in} stands for the volume of the inside house space, m_{fu} stands for the furniture mass, and c_{fu} stands for the specific heat of the wood furniture. The second term presents the heat transferred to the structure from the house interior

$$R^{n}_{N,j} = A_j h_{in}[(T^{n+1}_{in} + T^{n}_{in})/2 - T^{n}_{N,j}], \tag{11}$$

where h_{in} stands for the coefficient of convective heat transfer, T^{n}_{in} stands for the temperature of the inside air at time n, T^{n+1}_{in} the temperature of the inside air at time (n + 1), and $T^{n}_{N,j}$ stands for the temperature of the layer N at time n. When the temperature of the inside air is set to T_{tc} then $T^{n+1}_{in} = T_{tc}$.

The load for heating and cooling during a time interval Δt depends on the control strategies of the installation for heating and cooling. These strategies may be twofold:

1. The installation does not control the interior temperature when the device for heating or cooling does not operate.
2. The installation controls a constant interior temperature T_{tc} when the device for heating and cooling operates continually with variable power during defined periods.

When the first control strategy is applied, the load is $Q^{n}_{hc} = 0$. Then, temperature T^{n+1}_{in} is calculated by using Eq. (7)

$$T^{n+1}_{in} = \left\{ Q^{n}_{inf} + \sum_{j=1}^{6} Q^{n}_{sr,j} - T^{n}_{in}\left[h_{in}\sum_{j=1}^{6} A_j/2 - m_{in}c_{in}/\Delta t \right] + h_{in}\sum_{j=1}^{6} A_j T^{n}_{Nj,j} \right\} \Big/ \left[m_{in}c_{in}/\Delta t + h_{in}\sum_{j=1}^{6} A_j/2 \right]. \tag{12}$$

When the second control strategy is applied, the load Q^{n}_{hc} (negative for cooling) is calculated from Eq. (7) for known T_{tc} as:

$$Q^{n}_{hc} = m_{in}c_{in}(T_{tc} - T^{n}_{in})/\Delta t + \sum_{j=1}^{6} R^{n}_{N,j} - Q^{n}_{inf} - \sum_{j=1}^{6} Q^{n}_{sr,j}. \tag{13}$$

The load for heating and cooling of the house during a whole day is calculated as

$$D = (\tau_2 - \tau_1)\sum_{\tau_1}^{\tau_2} |\, Q^{n}_{hc} \,|, \tag{14}$$

where τ_1 is starting and τ_2 finishing time of simulation. The load for heating of the house during a whole day is

$$D_h = (\tau_2 - \tau_1)\sum_{\tau_1}^{\tau_2} |\, Q^{n}_{hc} \,|, \quad \text{for } Q^{n}_{hc} > 0, \quad \text{and} \quad D_h = 0 \quad \text{for } Q^{n}_{hc} \leq 0. \tag{15}$$

The mathematical model uses the following calculation procedure: first, assumed temperatures of the envelope layers and of the interior air are used as initial temperatures for beginning the first hour of simulation. Furthermore, the calculated temperatures at the end of the first hour of simulation are used as initial values for the next hour of simulation, and so on.

This mathematical model is stable if the first and second laws of thermodynamics are satisfied for every elemental volume of the house envelope.

3. Experimental validation

The results from [16] of an experiment conducted on 14 March 1992 are used for experimental validation of the numerical prediction. The experimental building model had a roof pitch angle $\theta = 30^\circ$. The envelope slabs of this experimental model consist of three layers: polyurethane, wood and polyurethane. Table 1 gives values of thickness, specific heat, density and thermal conductivity for each layer. All other details on the parameters of the building experimental model and other experimental conditions are given in [16].

4. Simulation

4.1. Simulation houses

Objects of the investigation are three weekend houses: two passive houses (PH), and one reference house (RH). The PH is characterized by the passive design; one wall is made from one-layer envelope, and other walls made from two-layer envelopes. The one layer envelope is entirely constructed from masonry, and the two-layer envelope is constructed from a masonry layer and from a thermal-insulation layer. Two PHs are investigated: winter passive house (WPH) and summer passive house (SPH). The WPH represents a PH with a one-layer wall facing south. The SPH represents a PH with a one-layer wall facing north. The RH is characterized by a non-passive design and used for comparison; its walls are entirely made from the two-layer envelope. The RH, WPH and SPH may have a two-layer envelope either with the masonry layer facing outside and thermal-insulation layer facing inside (denoted as MI houses), or with the masonry layer

Table 1
Properties of the envelope of the experimental model

Properties	Polystyrene	Wood
Thickness (mm)	20	20
Specific heat (J/kg-K)	700	800
Density (kg/m^3)	20	550
Thermal conductivity (W/m-K)	0.041	0.14

facing inside and thermal-insulation layer facing outside (denoted as IM houses). Their envelopes had an emissivity of $\epsilon = 0.5$, and values of the parameters of the envelope layers are given in Table 2.

All these houses were placed at 44° latitude and 185 m height above sea level; an average clearness factor was 70%. They had square plan of 10 m × 10 m, and 3 m height, with no windows or infiltration. The houses had their space–air temperature controlled at $T_{tc} = 20°$ from 8 h to 20 h.

4.2. Dependent variables

For the purpose of later illustrations five dependent variables were used:

1. Daily load P for heating and cooling of the PH; its value is equal to the value of D calculated from Eq. (14) for the PH.
2. Daily load R for heating and cooling of the RH; its value is equal to the value of D calculated from Eq. (14) for the RH.
3. Daily load P_h for heating of the PH; its value is equal to the value of D calculated from Eq. (15) for the PH.
4. Daily load R_h for heating of the RH; its value is equal to the value of D calculated from Eq. (15) for the RH.
5. Passive load fraction; its value is calculated in percents as

$$S = 100(R - P)/\mid R \mid . \quad (16)$$

The S is positive when the PH has a smaller daily load for heating and cooling than that of the RH; then, the use of the PH instead of the RH will save energy. The S is negative when the PH has a greater daily load for heating and cooling than that of the RH; then, the use of the PH instead of the RH will increase energy consumption.

4.3. Simulation cases

Heating and cooling loads of the houses were calculated for two days: for 10^{th} February and 15^{th} July. In the winter day, heating loads were calculated for two houses: the WPH and RH. The temperatures of house envelopes at the beginning of simulation (6 h) were the same as the outside temperature of 1.4°C. In the summer day, heating and cooling loads were calculated for two houses: the SPH

Table 2
Properties of layers of the envelope of the simulation houses

Property of envelope layer	Thermal insulation	Masonry
Specific heat, c (J/kg-K)	837	837.4
Density, ρ (kg/m^3)	400	1600
Thermal conductivity, k (W/m-K)	0.055	0.35

Table 3
Characteristics of investigation cases

House type	Investigation procedure	Thermal insulation faces	U-value of two layer envelope	y = thickness of thermal insulation
MI house	y = constant	outside	variable	0.03 m
MI house	U = constant	outside	0.713 $W/(m^2K)$	variable[a]
IM house	y = constant	inside	variable	0.03 m

[a] y is calculated from $y/k_{in}+x/k_{ms}=1/0.713$ where k_{in} stands for the thermal conductivity of thermal insulation, and k_{ms} stands for the thermal conductivity of masonry.

and RH. At the start of the simulation (6 h), the house envelopes temperatures were the same as the outside temperature of 19.37°C.

For both the winter and summer days two types of houses were investigated, and two investigation procedures were applied (Table 3). Types of houses investigated were IM houses and MI houses. For IM houses two investigation procedures were applied:

1. During the first procedure the thickness y of the thermal insulation layer was held constant, $y = 0.03$ m; then, as x was varied, the U value varied.
2. During the second procedure the U value of the two-layer envelope was held constant, $U = 0.713$ W/(m^{2}K); then, as x was varied, the y value varied.

For MI houses just one investigation procedure was applied where $y = 0.03$ m; then, as x was varied, the U value varied.

5. Results and discussion

5.1. Model verification

The model is verified by comparing the time functions of inside temperatures calculated by the ZID model, by the modified BRE-ADMIT model and those measured inside the experimental house. Fig. 3 shows that these values are very close to each other where the ZID model predicts the inside temperatures with the accuracy of ±1°C.

5.2. Winter-day simulation

Winter-day simulations show that the WPH and RH require heating for all values of x, i.e., $P = P_h$ and $R = R_h$. These results are reported in Figs. 4–6.

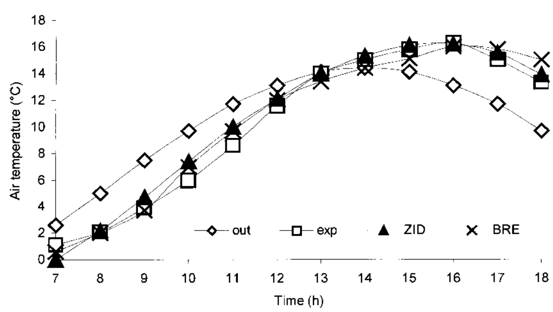

Fig. 3. Comparison of the calculated inside temperature (ZID by ZID model and BRE by BRE-ADMIT model) of the building with that measured (exp) for 14th March when $\theta = 30$°C. Here, "out" stands for outside temperature.

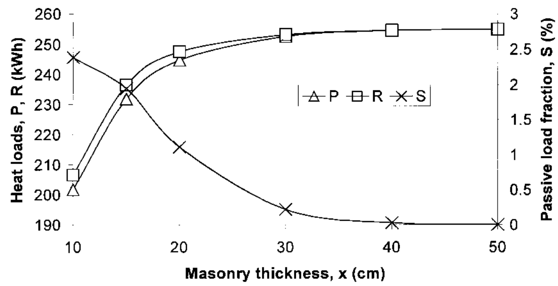

Fig. 4. Heat loads of the WPH and RH, and passive load fraction vs masonry thickness for 10th February. Here, thermal insulation faces outside; $y = 3$ cm.

5.2.1. IM houses — investigation procedure with y = constant

For the IM houses and the investigation procedure with y = constant, Fig. 4 shows the impact of the variation of the x on the P, R, and S. When the x increases, the P and R increase, i.e., the heat loads of the WPH and the RH increase. The reason is that the house envelope with the greater x has the greater mass and requires more heat to reach its operating temperature. Furthermore, when P and R are compared, it can be observed that for all x, $P < R$. Then, $S = 1.5\%$ on average, the S is higher when x is lower; the use of the WPH instead of the RH saves energy. When $x > 30$ cm, the WPH almost consumes the same amount of heat as the RH.

5.2.2. IM houses — investigation procedure with U = constant

For the IM houses and the investigation procedure with U = constant, Fig. 5 gives the impact of the variation of the x on the P, R, and S. The simulation results are similar to the results shown in the previous figure.

5.2.3. MI houses — investigation procedure with y = constant

For the MI houses and the investigation procedure with y = constant, Fig. 6

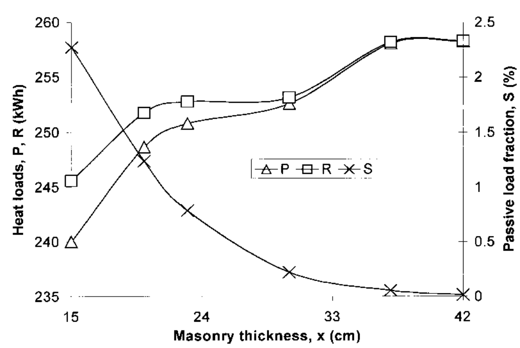

Fig. 5. Heat loads of the WPH and RH, and passive load fraction vs masonry thickness for 10th February. Here, thermal insulation faces outside; $U = 0.713$ W/m^{2}K.

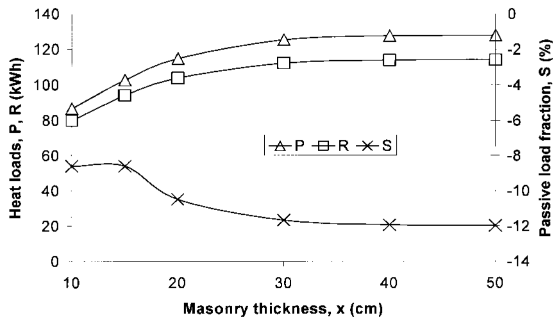

Fig. 6. Heat loads of the WPH and RH, and passive load fraction vs masonry thickness for 10[th] February. Here, thermal insulation faces inside; $y = 3$ cm.

gives the impact of the variation of the x on the P, R, and S. It is found that regardless of x there are $R < P$, and $S < 0$, so more energy will be used to heat the WPH than the RH.

5.2.4. IM house vs MI house

The P and R, heating loads, are smaller for the MI houses (Fig. 6) than for the IM houses (Fig. 4).

5.3. Summer-day simulation

Summer-day simulations generally show that the SPH and RH may require both cooling and heating, i.e., $P > P_h$, and $R > R_h$. These results are reported in Figs. 7–9.

5.3.1. IM houses — investigation procedure with y = constant

For the IM houses and the investigation procedure with y = constant, Fig. 7

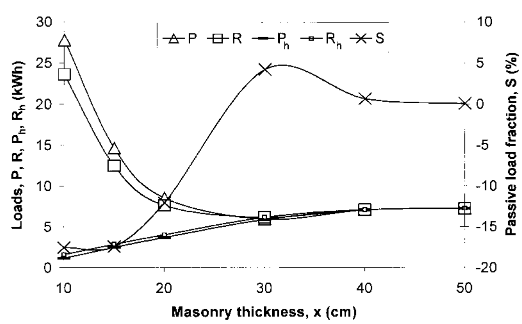

Fig. 7. Daily energy and heat loads of the SPH and RH, and passive load fraction vs masonry thickness for 15[th] July. Here, thermal insulation faces outside; $y = 3$ cm.

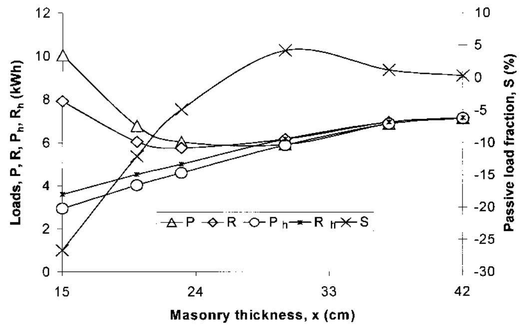

Fig. 8. Daily energy and heating loads of the SPH and RH, and passive load fraction vs masonry thickness for 15th July. Here, thermal insulation faces outside; $U = 0.713$ W/m^{2}K.

gives the impact of the variation of the x on the P, P_h, R, R_h, and S. When the P and P_h, and the R and R_h are compared it can be observed that:

1. $P > P_h$, $R > R_h$ for $x < 30$ cm. Then, the SPH and RH require both heating and cooling.
2. $P = P_h$ and $R = R_h$ for $x \geq 30$ cm. Then, both the houses require almost only heating.

When P and R are compared it can be observed that:

1. $P > R$ when $x \leq 27$ cm. This means that the SPH has a heating and cooling load higher than that of the RH; then, $S < 0$, and the use of the SPH instead of the RH loses energy.
2. $P < R$ when 27 cm $< x <$ 40 cm. This means that the SPH has a heating and cooling load lower than that of the RH. Then, $S > 0$, and the use of the SPH instead of the RH saves energy. The maximum of the S is around 4%; then, $x = 30$ cm.
3. $P = R$ for $x > 40$ cm. This means that the SPH has a heating and cooling load

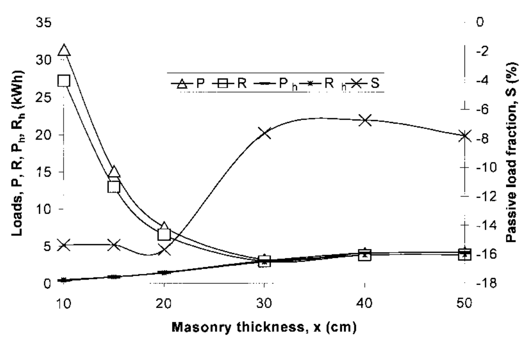

Fig. 9. Daily energy and heating loads of the SPH and RH, and passive load fraction vs masonry thickness for 15th July. Here, thermal insulation faces inside; $y = 3$ cm.

the same as that of the RH; then, $S = 0$, and the use of the SPH instead of the RH does not change energy consumption.

5.3.2. IM house — investigation procedure with U = constant

For the IM houses and the investigation procedure with U = constant, Fig. 8 gives the impact of the variation of the x on the P, P_h, R, R_h, and S. This figure gives similar results as the results shown in the previous figure.

5.3.3. MI house — investigation procedure with y = constant

For the MI house and the investigation procedure with y = constant, Fig. 9 gives the impact of the variation of the x on the P, P_h, R, R_h, S, and S_h. When P and P_h, and R and R_h are compared it can be observed that:

1. $P > P_h$, $R > R_h$ for $x < 30$ cm. Then, the SPH and RH require both heating and cooling.
2. $P = P_h$ and $R = R_h$ for $x \geq 30$ cm. Then, both houses require almost only heating.

This figure shows that, regardless of x, passive energy saving is not possible. For all x, the SPH has a heating and cooling load greater than that of the RH.

5.3.4. IM house vs MI house

Cooling and heating loads are smaller for the MI house (Fig. 9) than for the IM houses (Fig. 7).

6. Conclusion

Questioning the solar energy use through the passive design of weekend houses in Yugoslavia, this paper demonstrates cases where different house design either may yield or may not yield reduction in the loads for heating and cooling. Specifically, the paper reveals that:

1. When the layer of thermal insulation faces outside of the house (IM house) the removing of thermal insulation from one wall may decrease a load for heating and cooling.
2. When the layer of thermal insulation faces inside of the house (MI house), the removing of thermal insulation from one wall does not decrease a load for heating and cooling.
3. The loads for heating and cooling are smaller for the MI house than for the IM house.

Furthermore, for the IM house this paper reveals that:

1. For the winter day, the decrease in the load of 1.5% on average is recorded for all values of masonry thickness and for both the investigation procedures when

the thickness of thermal insulation remains the same and when the coefficient of U value of wall remains the same.

2. For the summer day the highest decrease of around 4% in the load for heating and cooling is obtained for the value of masonry thickness of 30 cm when both the simulation procedures are applied.

This means that government and the construction industry in Yugoslavia should carefully review and evaluate their energy saving policies and alter national building codes to fully benefit from the passive use of buildings. However, all solutions should be questioned for optimum economy and for any operational restrictions that may arrive such as to support good propagation of humidity through the building envelope.

Appendix

The outside air temperature

During the day, the outside air temperature changes according to sine function

$$T^{\mathrm{n}}_{\mathrm{ou}} = a_{\mathrm{t}} \ \sin(\tau\pi/12 + 17\pi/12) + b_{\mathrm{t}} \tag{A1}$$

with the maximum temperature at 1 pm and minimum temperature at 1 am. Here, a_{t} is the amplitude of the daily variation of outside temperature of air, b_{t} the mean value of outside temperature of air during the day. For this simulation it is assumed for the winter day $b_{\mathrm{t}} = -0.4°\mathrm{C}$ and $a_{\mathrm{t}} = 3.85°\mathrm{C}$ and for the summer day $b_{\mathrm{t}} = 21.1°\mathrm{C}$ and $a_{\mathrm{t}} = 6.6°\mathrm{C}$.

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