EXPERIMENTAL STUDIES AND ECONOMIC CONSIDERATIONS ON A LIVING SPACE HEATED THROUGH PASSIVE SOLAR GAIN AND THROUGH ELECTRIC POWER

by

Ioan LUMINOSU

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The Trombe wall, of an area $A_T = 8.8\ m^2$, built on the southern facade of a room, heats the accommodation during the transition months, complementary to electric power. The statistical processing of the experimental data led to a global quantitative image of the wall's behavior during the average day of the months March, April, September, and October 1999. The inner climate parameters are: $t_{int} = 21$ °C, $t_{rad} = 17.9$ °C, $t_{room} = 19.5$ °C, $\varphi = 35\text{-}70\%$, $E \in (80\text{-}120)$ lx. The thermal comfort factor is $B = -0.325$. These values insure a room's comfort close to the optimal one prescribed by hygienists. The heliothermal conversion's efficiency is $\eta_T = 10.4\%$. The proportion of heat supplied by the wall in the entire energy required by the room is $\eta_{heat} = 45.8\%$. The wall's specific cost is $c_u = 39.4$ € /m². The write-off period of the initial investment is $n_1 = 53$ years. The development of passive solar architecture in the Euro-region Danube-Kris-Mures-Tisa which includes the town of Timisoara (45° north, 22° east), was proven feasible by experiments from both the energy and the economical point of view.

Key words: passive solar heating, Trombe wall efficiency, on site measurements, feasibility

Introduction

The Trombe-Michele wall is the main element of the installation destined for building heating through passive solar gain.

In what follows we present some significant conclusions and achievements on the heating through delayed solar gain, as they are described in the specialized literature.

Given the conditions $t_{ext} = 0$ °C, $t_{int} = 20$ °C, the wall without sun effect transfers heat towards the interior if $G_{sn} \geq 465.2$ W/m² [1]. This condition is met in Romania, during the transition months, between the 11-13 hrs daytime.

In order to increase the wall's contribution to the energy required by the room and to decrease the nocturnal energy losses, the wall is covered with a glass plate during daytime, and additionally with a curtain during nighttime 10 . The wall is efficient this way, when $G_{sn} \geq 200$ W/m^2. As consequence the operation period extends to the 10-18 hrs average daytime.

The solar panels mounted on the eastern and southern facade of a school supplied each year the thermal energy of 2468 kWh, during classes 5 .

The contribution of the heat supplied by a passive wall to a university building was 20% of the whole energy used during winter 15 . The passive wall has its greenhouse fitted with a transparent insulator plate 100 mm thick.

The prefab multiplayer opaque facades increase the passive wall's efficiency with up to 16-21% 9 .

The "Skyterm" system described in 4 uses water-filled barrels as heating or cooling elements, as needed. The barrels are mounted on the building's roof and they are covered with transparent plates during cold and cloudless days, respectively with insulating plates during sultry or no insolation days.

This paper presents a pilot installation fitted with Trombe wall, built at "Politehnica" University of Timisoara. The studies aimed at establishing the opportunity of implementing passive solar installations for building heating in the western part of Romania. The installation built in 1985 has undergone many tests since then, and aspects of its behavior are described in the papers 7, 8, 11-13 .

The installation was used for solar heating of a living room, complementary to electric power, during the transition months (March, April, September, and October).

This paper presents the facility's components, the average values for the inner climate parameters, the comfort factor, its efficiency and some economical considerations.

This experimental study can prove useful to helio-technical installations designers in the Euro-region Danube-Kris-Mures-Tisa, knowing that settlements in this area have the same climate as the town of Timisoara.

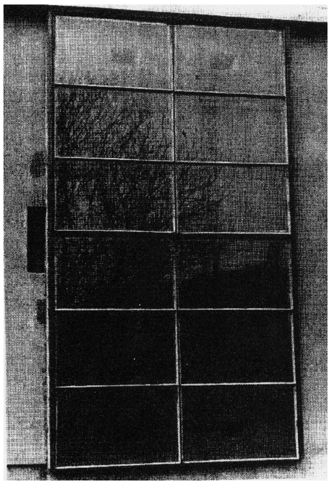

Figure 1. Photo of a Trombe wall module

Experimental installation description

The Trombe wall is installed on the southern facade of a room belonging to a classical building with four rooms at the ground floor. Figure 1 shows a module of the solar radiation collector wall. The building has a reinforced concrete ledged roof, bitumen insulated.

The room 's walls

The room's dimensions are 2.80 × 4.75 × 1.75 m, and those of the window are 1.0 × 0.75 m. The brick walls, 0.39 m thick, are plastered with lime and gesso mortar. The concrete foundation is one meter (h =

= 1 m) deep and 0.49 m thick. The underground water nape lies at depth smaller than four meters, and has a temperature of t_f = 10 °C.

Figure 2 shows the building's blueprint, with: R_{sn} – room fitted with passive wall, $R_{1,\,2}$ – electrically heated rooms, K – kitchen, BR – rest room, H – hall, $W_{1\text{-}5}$ – wooden double windows, $D_{1\text{-}6}$ – doors, and W_T – Trombe wall. Throughout the measurements all the rooms $R_{1,\,2}$, K, BR, and H, had a controlled level of temperature around t_{int} = 21 ± 1 °C, with the help of thermostat fitted electric heaters. This insured thermal fluxes through the adjacent walls equal to zero. The level of temperature in the R_{sn} room was maintained at a 21 ± 1 °C level through solar gain and electric power.

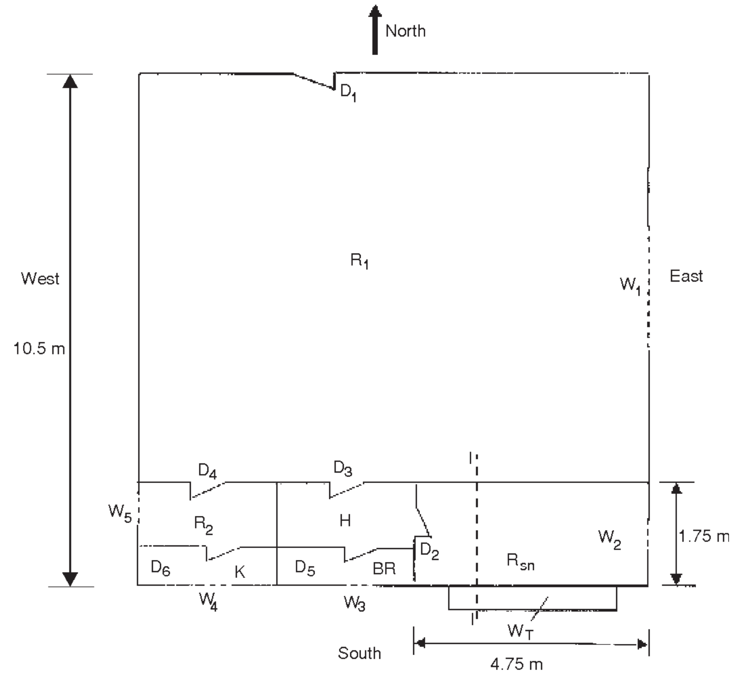

Figure 2. Building's blueprint

The Trombe wall

Two modules form the Trombe wall, with a total area of A_T = 8.8 m^2 (fig. 3). The external side of the W_T wall is painted in black. The greenhouse effect is created by a 5 mm thick glass plate (S on fig. 3), secured in a metallic frame, $(\tau\alpha)_{eff}$ = 0.80. The collector's thermal losses factor is U_L = 8.40 W/m^2K. The curtain from I (fig. 3) covers the wall during night time or sultry days.

The air dampers $L_{1,2,3}$ (fig. 3) insure the direction of the airflow through the wall's grommets, as set by the user.

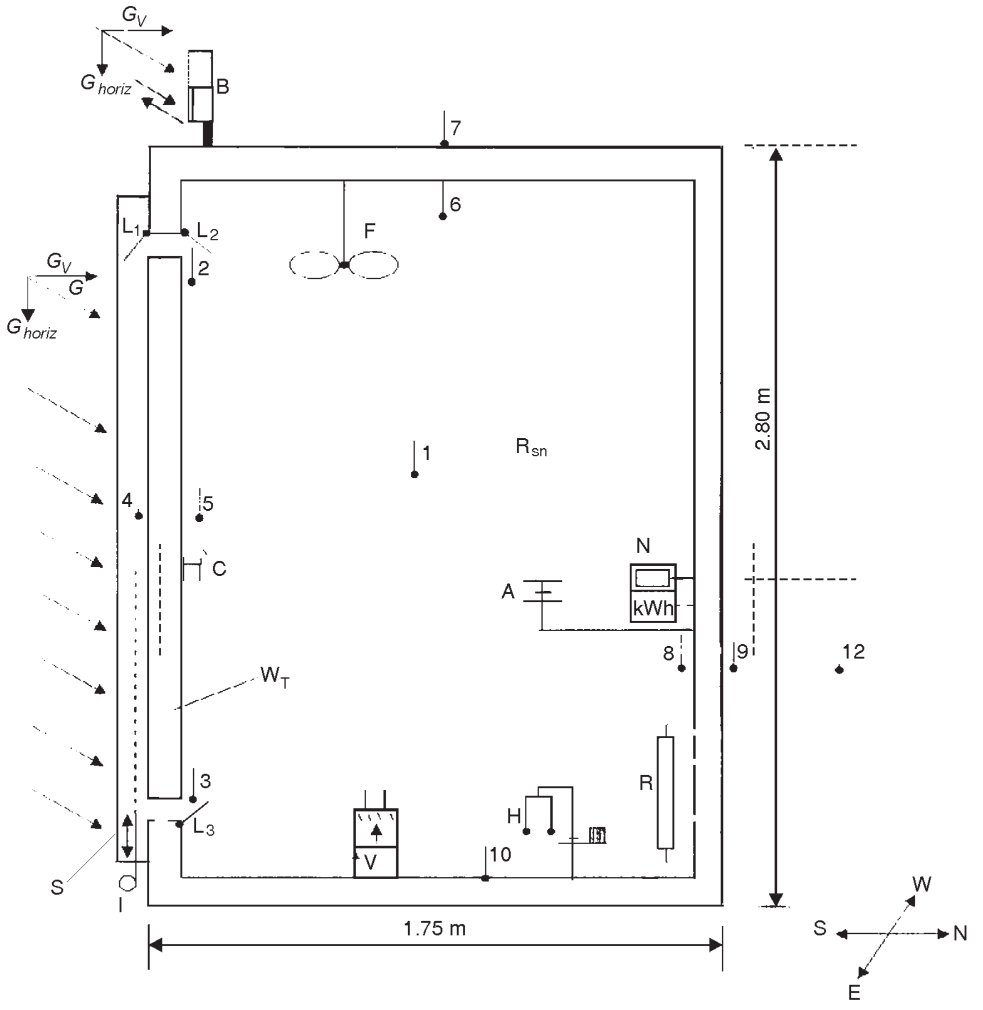

Figure 3. Chart of the Trombe wall room and measuring points (vertical cross section I–I)

The water container C (fig. 3) attached on the passive wall, fitted with a cover, insures the inside air humidity.

The small power fan (P = 10 W) insures the thermal field's uniformity. The thermostat fitted radiator R and the W_T wall provide the room's heating. The heat supplied by the wall and the radiator balances the room's thermal losses through the eastern wall, the ceiling, the floor and the window. The cool air from the outside penetrates the room only through the window's joints.

The lighting is provided by a Philips Ecotone light bulb, P = 12 W.

Measuring devices

The temperature in points 1 to 12 marked on fig. 3, was measured with the help of a multichannel electronic thermometer, described in 2 . The temperature transducers were the Zener diodes, and the reading was provided by the milivoltmeter V, with an error of ±0.1 °C. The thermometer 1 shows the temperature $t_1 = t_{int.}$ The thermometers 4 to11 show the walls' sides temperatures, while the thermometer 12 shows the temperature $t_{12} = t_{ext}$. The thermometers 2 and 3 show the temperature of the air flowing through the grommets. The thermometers 2 to 11 have their Zener diodes buried in mortar at a depth of 10 mm.

The global solar radiation intensity on the wall's surface was measured with a self-balanced differential bolometer, described in 12 , fitted with a vertical transducer placed in point B, fig. 3. The measurement's error was ±5%.

The electric power used by the room was read on the electricity meter aem1CM4A, placed in point N on fig. 3, with an error of ±5 Wh.

The air's relative humidity was measured on the Assman psychrometer (hygrometer) H on fig. 3, with a relative error of ±5%.

The lighting in the center of the room, in horizontal plane, was measured with the LuxPU150 light meter, of a 10% margin.

The air streams' velocity, one meter away from the grommet L_2 on a North-South direction, was measured with the FEET anemometer marked A on fig. 3, with an error of ±10%.

Analytic model

Hypotheses

The analytic model is developed based on the following hypotheses:

- the natural flow of the hot air following the direction $L_3 \rightarrow L_2 \rightarrow R_{sn} \rightarrow L_3$ takes place between 10-20 hrs, because during this period the greenhouse air temperature is bigger than the inside one with at least 5.6 °C,
- the passive wall radiates heat towards the room during the interval 10 to 22,
- the net thermal flux through the walls between room R_{sn} and the adjacent rooms is zero, as the rooms have the same temperature,
- the R_{sn} room loses heat through transmission, through the eastern wall, the ceiling the floor and the window's gap,
- the air coming into the room when opening the door D_2, and through its louvers, has the same temperature as the room, so $\dot{Q}_d$ 0,
- the cold air infiltrating through the window's joints , of a $L = 3.5$ m length, must be heated up to $t_{int} = t_1 = 21$ °C, and
- the underground water nape has a depth $h < 4$ m and the temperature $t_f = 10$ °C.

The heat lost by the room

The heat quantities lost in time unit, $\dot{Q}$, through various processes are given by the following equations 13 :

- the heat lost through transmission (conduction and convection), through the eastern wall, the ceiling, the floor and the window's gap is 14 :

$$\dot{Q}_t \qquad m_i A_i \frac{\bar{t}_1 \quad \bar{t}_{12}}{R_i} \tag{1}$$

where $t_1 = t_{int}$ and $t_{12} = t_{ext}$,

- the heat lost through the ground is:

$$\dot{Q}_{eh} \quad A_{fl,w} \frac{\bar{t}_1 \quad \bar{t}_f}{R_{eh}} \quad A_{cr} \frac{\bar{t}_1 \quad \bar{t}_{12}}{R_{cr}} \tag{2}$$

- the heat required to heat the air infiltrated from the outside through the windows leakiness is:

$$\dot{Q}_{wd} \quad E(iL)v^{4/3}(\bar{t}_1 \quad \bar{t}_{12}) \tag{3}$$

where $E = 1$ for the given case, the ground floor, the wind velocity is $v = 3.4$ m/s, and the air infiltration factor is $i = 0.035$ W(s/m)$^{4/3}$/m·K .

The physical meanings of the parameters from eqs. (1), (2), and (3) are:

m_i – thermal massiveness coefficient of the construction element,
A_i – area of construction element, through which the heat is lost,
R_i – global thermal resistance to thermal permeability through the construction element,
$A_{fl,w}$ – total area of the floor and external walls in direct contact with the ground,
R_{eh} – global thermal resistance of the ground, and
A_{cr} – area of the perimeter band, 1 m in width, laid on the ground along the external walls.

The values of the parameters A, R, and m, for the studied room, are given in tab. 1.

Table 1. Values for parameters *A, R,* and *m*

Parameter / Constr. element	A m^2	R m^{2}K/W	m
Eastern wall	4.15	0.91	0.90
Ceiling	8.31	0.82	1.05
Window	0.75	0.43	1.20
Floor + external wall	14.81	–	–
Ground	–	3.72	–
Perimeter band	7.30	0.42	–

The total heat lost by the room in time unit, through all the construction elements is:

$$\dot{Q}_L \quad \dot{Q}_t \quad \dot{Q}_{eh} \quad \dot{Q}_{wd} \tag{4}$$

The hourly heat lost by the room is:

$$Q_{h,L} \quad 3600\dot{Q}_L \tag{5}$$

The daily heat lost by the room is:

$$Q_{d,L} \quad \overset{12}{\underset{1}{}} Q_{h,L} \tag{6}$$

The room's hourly energy balance is:

$$Q_{h,L} \quad Q_{h,T} \quad Q_{h,el} \tag{7}$$

where $Q_{h,T}$ is hourly heat supplied by the Trombe wall to the room.

Equation (7) gives the hourly heat supplied by the Trombe wall. The daily heat of the Trombe wall is given by eq. (8):

$$Q_{d,T} \quad \overset{12}{\underset{1}{}} Q_{h,T} \tag{8}$$

Experimental results

The measured parameters were: the radiation flux density in vertical plane, G_v Wm^{-2} , the inside air temperature $t_{int} = t_1$, the outside air temperature $t_{ext} = t_{12}$, the louver's air temperature t_2 and t_3, the walls' sides temperatures t_4 to t_{11}, the air's relative humidity, φ % , the lighting in the center of the room in horizontal plane, E lx , the air streams' speed one meter away from the louvers, v m/s .

The measurements were carried out each hour, from 10 to 22 hrs during the months of March, April, September, and October 1999, six clear-sky days each month.

In order to otbain a global quantitative image of the facility' behavior we calculated the arithmetical means of the hourly parameters, for the average day; *e. g.*

$$\bar{t}_h \quad \frac{1}{n}\overset{n}{\underset{1}{}} t_{h,j}, \qquad \overline{G}_h \quad \frac{1}{n}\overset{12}{\underset{1}{}} G_{v,j}, \qquad n \quad 24, \qquad i \quad \overline{1,24}$$

The hourly mean radiant flux is given by eq. (9):

$$\overline{\Phi}_h \quad \overline{G}_h A_T \tag{9}$$

The hourly mean radiant energy is calculated with eq. (10):

$$\overline{Q}_{h,sn} \quad 3600\overline{\Phi}_h \tag{10}$$

The daily mean radiant energy during 10-18 hrs is given by eq. (11):

$$\overline{Q}_{d,sn} \quad \overset{8}{\underset{1}{}} \overline{Q}_{h,sn} \tag{11}$$

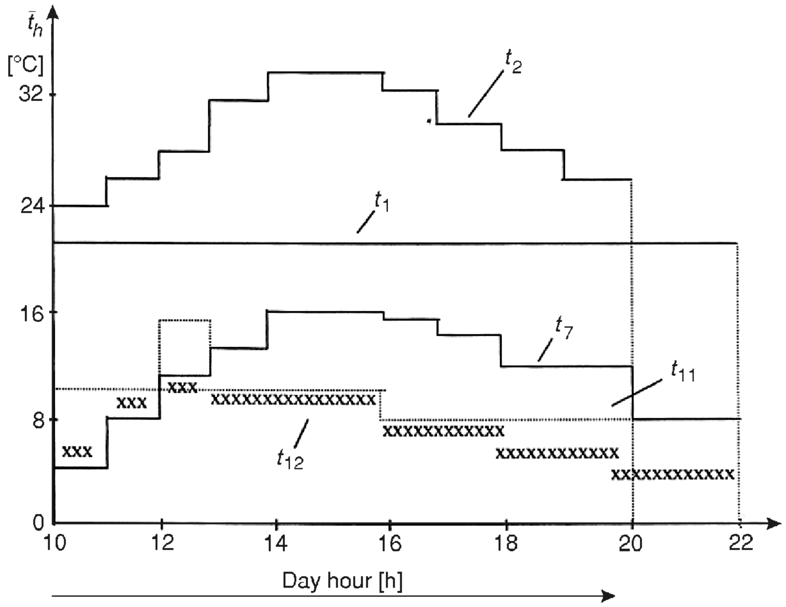

Figure 4. Hourly average temperatures

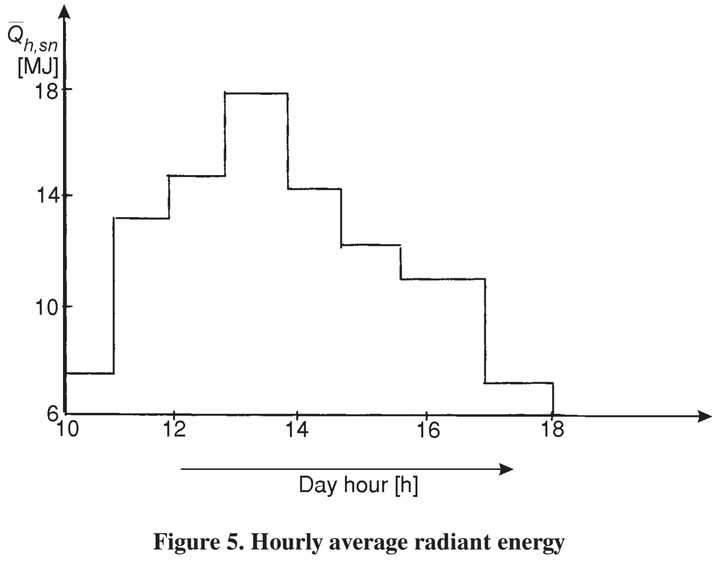

Figure 5. Hourly average radiant energy

Figure 4 shows the daytime variation of the hourly average temperatures at the upper louver (t_2), in the center of the room (t_1), on the external side of the ceiling (t_7), on the external side of the eastern wall (t_{11}), and that of the outside air (t_{12}).

The temperature of the inside air is 21 °C, it reaches 32 °C at the upper louver, has a variation between 5-12 °C on the outside and is 4-6 °C smaller than the inside temperature, on the inner sides of the walls, due to the wall effect.

Figure 5 shows the variation of the hourly average radiant energy, $\overline{Q}_{h,sn}$, in the interval 10-18 hrs. The daily average radiant energy is $\overline{Q}_{d,sn}$ 99.1 MJ.

Figure 6 shows the variation of the hourly average heats: the heat lost by the room, $\overline{Q}_{h,L}$, the electric power used by the room for heating and lighting, $\overline{Q}_{h,el}$, and the heat supplied by the Trombe wall, $\overline{Q}_{h,T}$, in the interval 10-22 hrs.

Adding up the hourly heats results in the following total daily heats: the heat lost by the room $\overline{Q}_{d,L} = 22.4$ MJ, the heat supplied by the passive wall $\overline{Q}_{d,T} = 10.26$ MJ and the electric power used $\overline{Q}_{d,el} = 12.31$ MJ. The wall's useful power is $P_T = 237.5$ W. The number of clear-sky days during the transition months is $N = 46$. The annual heat supplied by the wall is $Q_{y,T} = NQ_{d,T} = 131$ kWh.

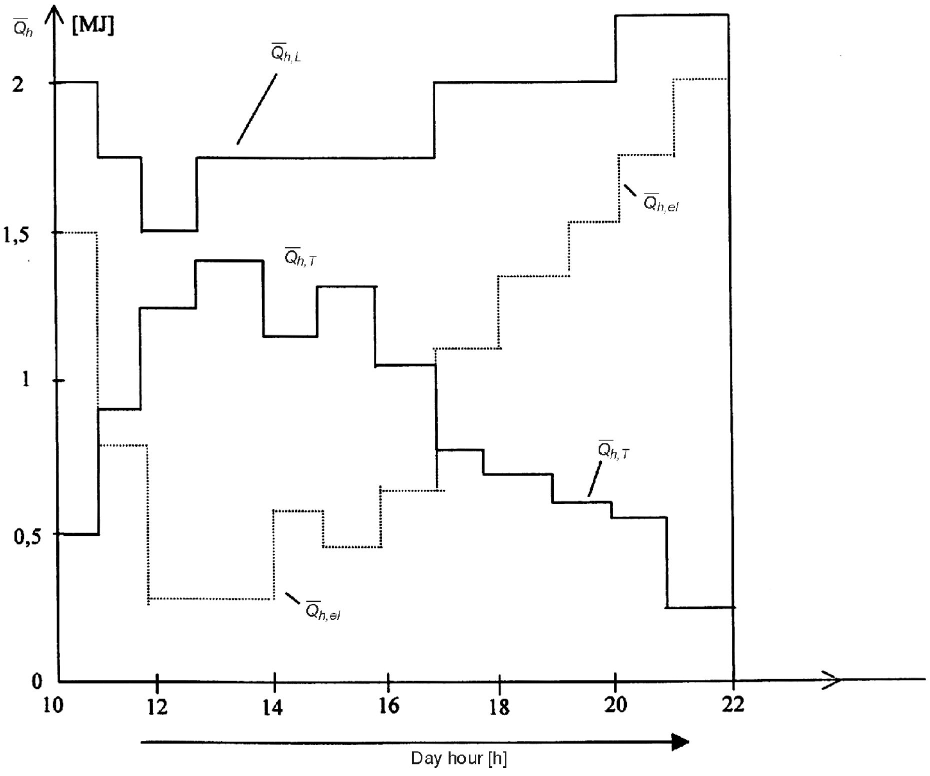

Figure 6. Hourly average heats exchanged by the room

The efficiency of solar energy conversion for the passive wall is:

$$\bar{\eta}_T = 100\frac{Q_{d,T}}{Q_{d,sn}} = 10.4\% \tag{12}$$

The wall's efficiency in heating the room, in the interval 10-22 hrs is:

$$\bar{\eta}_{heat} = 100\frac{\bar{Q}_{d,T}}{Q_{d,L}} = 45.8\% \tag{13}$$

The wall's specific annual heat is $q_{y,T} = \dfrac{Q_{y,T}}{A_T} = 149\ \mathrm{kWh/m^2}$

The velocity of the airflow through the room was $\bar{v} = 0.15$ m/s, *i. e.* the upper comfort limit in which concerns the moving air.

Thanks to the water-container attached on the Trombe wall, the air humidity was kept in the limits of 35-70%, a range well inside the humidity comfort limits.

The center of the room enjoyed lighting in the range of 50-70 lx in horizontal plane, by operating the blinds and using the 12 W ECOTONE light-bulb turned on for about 4 hrs a day.

Thermal comfort in the room

The thermal comfort feeling is given by the inside air temperature and by the temperatures of the walls and of the other objects the human body establishes a radiant energy exchange with.

According to hygienists, [14], the radiant temperature is given by eq. (16), and the room's temperature by eq. (17):

$$t_{rad} = \sum_{1}^{j} f_j t_j \tag{16}$$

$$t_{room} = \frac{t_{int} + t_{rad}}{2} \tag{17}$$

where j is the number of elements that the body establishes radiant energy exchange with, and f_j are the shape factors,

$$f = \frac{1}{A}\sum_{1}^{j} A_j \quad (A\text{ – exchange area})$$

The level of comfort is optimal when the room's temperature given by (17) has the same value as the comfort temperature prescribed by the hygienists.

According to Brodke [13], an inside air temperature of $t_{int} = 21$ °C must have a correspondent of $t_{rad.adm} = 16.3$ °C in radiant temperature and of $t_{comf} = 18.7$ °C in comfort temperature.

Table 2. Thermal comfort inside the room

Radiant element	f	$\bar{t}_j$ [C]	$\bar{t}_{rad}$ [C]	$\bar{t}_{room}$ [C]
Eastern wall	0.09	16		
Southern wall	0.24	26		
Western wall	0.09	18	17.9	19.5
Northern wall	0.24	18		
Ceiling	0.16	14		
Floor	0.16	13		

Table 2 gives the shape factors, f_j, the average temperatures of the walls' sides, the average radiant temperature $\bar{t}_{rad}$, and the room's temperature .

The Trombe wall produces an increase in the room's temperature with 0.8 °C over the comfort temperature prescribed by the hygienists.

The thermal comfort factor, according to Van Zuilen 14 , is given by eq. (18):

$$B \quad C \quad 0.25(\bar{t}_{int} \quad \bar{t}_{rad}) \quad 0.1\bar{x} \quad 0.1(37.8 \quad \bar{t}_{int})v^{½} \tag{18}$$

with: x – absolute humidity of the inside air, $\bar{x}$ = 12 g/kg,

C – constant taking into account the season; for the given case C = –10.6, and

v – air velocity.

The thermal comfort feeling, depending on the values for B, can be optimal (B = = 0), satisfying (B = ±1), or discomforting (B = ±3).

B = –0.325 for the given case, meaning that the comfort reaches an optimal state.

Economical considerations

In what follows we present a rough but simple financial evaluation of the installation. For estimation we used the prices in Romania, at the rate of exchange from March 2002.

The expenses on chapters are as follows:

- materials, c_1 = 92 □;
- labor, c_2 = 83 □;
- social, c_3 = 71 □;
- indirect, c_4 = 32 □;
- producer's benefit, c_5 = 14 □;
- value added tax, c_6 = 55 □.

The total investment is:

$$I \quad {}^{6}_{1} c_i \quad 347\,\square, \qquad i \quad \overline{1.6} \tag{19}$$

The walls's unit price is $c_u = I/A_T = 39.4$ □/m^2.

The initial investment for one installed kilowatt is:

$$i \quad \frac{I}{P_T} = 1461 \ \square/\text{kW} \tag{20}$$

The next evaluations take into account the small investment, meaning that there is no need for bank loans.

The energy used for comparison is the electric power.

The unit cost of electric power is $c_{el} = 0.07$ □/kWh.

The annual cost savings for the comparable energy are:

$$E_m = Q_{y,T} c_{el} = 9.2 \ \square \tag{21}$$

The annual specific monetary savings are:

$$e_m \quad \frac{E_m}{A_T} \quad 1.04 \ \square/\text{m}^2 \tag{22}$$

The annual specific expenses for maintenance are $c_7 = 0.3$ □/m^2.

The write-off period of the initial investment is given by eq. (23), 13 :

$$c_u + n_1 c_7 = n_1 e_m \tag{23}$$

and the result is $n_1 = 53$ years.

The installation's lifetime equals that of the building is $n_2 = 100$ years.

The specific cost of 1 kWh supplied by the Trombe wall during the interval n_2 is:

$$c_8 \quad \frac{I}{Q_{y,T}} n_2 \quad 0.026 \ \square/\text{kWh} \tag{24}$$

The cost difference $\Delta c = c_{el} - c_8 = 0.044$ □/kWh is in the favor of the user.

After the investment's write-off the wall produces the benefit given by eq. (25), 3 :

$$B = (n_2 - n_1) E_m = 432 \ \square \tag{25}$$

The ratio between benefit and investment $r = B/I = 1.24$ is in the favor of the solar energy user.

Discution

The useful daily specific heat of the Trombe wall is $q_d = 10.2$ MJ / 8.8 m^2 = = 1.16 MJ/m^2. We can install Trombe walls of an area $A' = 30$ m^2 on the facades exposed to solar radiation, belonging to family houses, with small expenses.

The heat quantity supplied each year by the passive walls would be $Q_{u,T} = Nq_dA' = 444.7$ kWh representing a 46% ratio from the electric power used for heating during the clear-sky days of the transition months.

Considering the present cost of electric power, the annual family cost savings would be $E = c_{el}Q_{u,T}$ □/year.

The predictable increase of the electric power cost up to the value $c'_{el} = 0.08$ □/kWh would lead to an increase in the costs savings to the value $E' = 35.6$ □/year, and it would reduce the investment's write-off period to a time interval of $n' = 44$ years.

Regular people and legal persons (institutions) too would take a great benefit from the development of passive solar architecture in the Euro-region that includes the town of Timisoara. The activities in institutions are carried out mainly during the insolation period of the day. And further more, legal persons benefit of a deduction in the value added tax resulting in a unit cost decrease with up to 6.25 □/m^2.

This paper is open for further study, considering a fraction of the passive wall fitted with a radiation absorbing metal plate. The air gap between the wall and the plate would insure a flow of hot air meant to heat the room during the insolation period of the day. The uncovered portion of the wall would heat the room only after sundown, by delayed solar gain.

Another option would consist in equipping the Trombe wall with automatized installations. This would allow the facility to operate in covered-sky days too, by using the solar energy form all the hours of sun brightness in the sky.

Acknowledgment

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Nomenclature

A – area, m^2
– anemometer,
B – comfort factor, –
– monetary benefit, □
BR – rest room,
C – season specific factor, –
C – container
c – cost, □
D – door
E – lighting multiplying factor, lx
e – monetary specific savings, □/m^2
F – fan,
f – shape factor, –
G – global radiation intensity, W/m^2

H – halls
– hygrometer
h – concrete foundation deepness, m
I – financial investment, □
i – infiltration factor, W(s/m)$^{4/3}$/mK
– specific expenses, □/kW
K – kitchen
L – length, m
– perimeter length, m
m – thermal massiveness coefficient, m^{2}K/W
N – number of clear-sky days, –
n – number of measurement days, –
– number of years, –
P – power, W
Q – heat quantity, J
– radiant energy, J
q – thermal specific energy, J/m^2
R – global thermal resistance, m^{2}K/W
R – room
– radiator
r – ratio between monetary benefit and investment, –
S – glass plate
t – temperature, °C
U – thermal factor, W/m^{2}K
v – wind velocity, m/s
V – voltmeter
W – window,
– wall
x – absolute humidity, g/kg

Greek letters

Δ – finite diference
η – efficiency
$\tau\alpha$ – equivalent product absorption-transmission
φ – relative humidity
Φ – radiation flux

Subscripts

comf – comfort
cr – perimeter
d – daily
– door
eff – effective
eh – earth (soil)
ext – exterior
f – underground water
fl – floor
h – hourly
heat – heating
i – number of day

– construction element
int – interior
j – radiant surface
– construction element
L – loss
m – monetary
rad – radiant
sn – solar
T, T – Trombe
t – transmission
u – unitary
v – vertical
w – wall
wd – window joints
y – annual
1–12 – measurement points

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Author's address:

I. Luminosu
Department of Physics, Universitatea "Politehnica"
P-ta Regina Maria Nr. 1
1900 Timisoara, Romania
E-mail: ioan.luminosu@europe.com

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