PERFORMANCE EVALUATION OF THERMAL STORAGE POROUS WALL WITH VENTS USING PASSIVE SOLAR ENERGY

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ABSTRACT

The performance of thermal storage porous wall with vents (gravel material) is analyzed for passive solar heating system under Baghdad climatic conditions by comparing it with conventional wall (Concrete wall) for a variety of control strategies. The variation has been calculated during a period of heating season for three months from December (1999) to February (2000) by using computer simulation with **MATLAB** language (Ver.6.5). A mathematical model containing the governing differential equations of heat transfer through the wall and glazing under unsteady heat flow was performed by using "control volume" technique to obtain the temperature distribution within the wall. The study was carried out for a south facing vertical wall and the effect of different thicknesses, porosities, effect of insulation and glazing layers and effect of vents was also investigated.

الخلاصة

تم تحليل أداء جدار الخزن الحراري المسامي ذو تهوية (مادة الحصو) بالاستخدام السلبي للطاقة الشمسية تحت الظروف المناخية لمدينة بغداد بمقارنته بجدار تقليدي مصنوع من الكونكريت لعدد من الإستراتيجيات المسيطر عليها. تم حساب التغيرات أثناء موسم التسخين ولثلاث شهور من كانون الأول (١٩٩٩) إلى غاية شباط (٢٠٠٠) باستخدام الحاسوب وبمساعدة لغة MATLAB (النسخة 6.5). تم تكوين المعادلات التفاضلية الحاكمة لانتقال الحرارة خلال الجدار و الزجاج باعتبار أن سريان الحرارة متغيرة مع الزمن وذلك باستعمال طريقة تدعى "الحجم المسيطر" للحصول على توزيع درجات الحرارة خلال الجدار, تمت الدراسة على جدار عمودي وأُخذ بنظر الاعتبار أسماك وقيم للمسامية مختلفة, إضافة إلى تأثير وضع عازل ليلي وتأثير وجود التهوية خلال الجدار

KEYWORD

Thermal storage, Passive solar, Trombe wall, Porous wall

INTRODUCTION

Passive solar heating systems , collect and utilize solar energy by natural means and generally exclude the use of mechanical power or electric controls to regulate the flow of heat.

The thermal energy is transferred in and out of the structure, in and out of the storage medium and around it, and through the conditioned space by natural means.

A passive solar heating system has four features that distinguishes it from a conventionally heated one , since the sun is a primary source of heat ,a passive solar design includes (Ralph 1980) :

- A method to collect solar energy.
- A way to store that energy.
- A system to release energy in the form of heat to the living space "room".
- A means for controlling the heat that reaches the living spaces.

(Nayak 1983) developed a mathematical model to analyze the thermal performance of some typical passive heating concepts, mainly the Trombe wall. The model yields analytical expression for the time dependent heat flux entering the living space. (Aung 1972) investigate the effect of asymmetric heating on the free convection heat transfer in parallel plates vertical channel. The average Nusselt number was found to be related to the Rayleigh number very nearly by a universal curve for all temperature difference ratios. The theoretical results were verified by experimental measurement.

(Ohanessian 1978) perform a comparative analysis between Trombe wall and conventional heated house over atypical 28 day Melbourne winter period. Saving of 40 percent interims of energy of energy costs was obtained. (Casperson 1979) provided experimental information regarding the heat transfer characteristic of the collector wall system. The data collected provided some usful information and interested trends.

THERMAL STORAGE BY POROUS WALL

The type of thermal storage wall can be divided into three kinds:

1. Masonry wall.

2. Water wall.

3. Porous wall.

To formulate the mathematical model of this problem, one dimensional heat flow has been considered, and homogeneous layer with constant properties has been assumed (Al Mashat S M 1999).

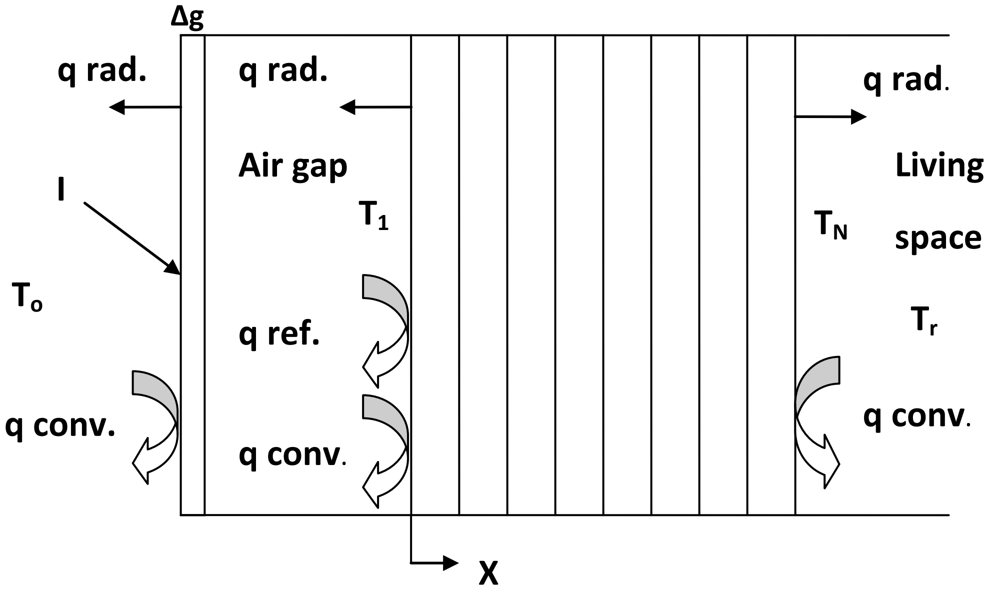

Fig. 1. Schematic of Wall Energy Balance

The energy equation through the porous wall layers shown in Fig. (1) Can be written as (Warren 1973)

$$\frac{\partial}{\partial x}\left(K_e \frac{\partial T}{\partial x}\right) = [\emptyset(\rho C)_f + (1-\emptyset)(\rho C)_s]\frac{\partial T}{\partial t} \qquad (1)$$

Where K_e is the thermal conductivity of thermal storage porous wall.

The differential equations can be changed to discretization equations by using a numerical method called "Control Volume Technique". Details of this method explained by reference (Patanker 1980). This by integrating equation (1) over a control volume as shown in Fig. (2)and over a time interval from t to t+Δt, yield to discritization equation.

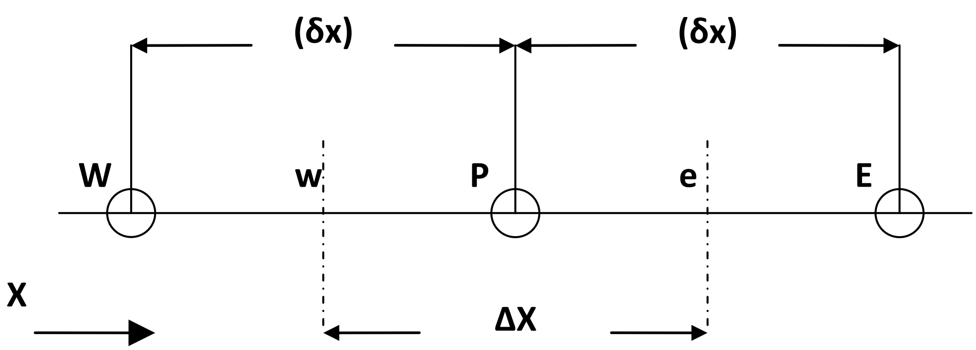

Fig. 2. Grid point cluster for one dimensional problem

Equation (1) can transfer to the following discretization equation by which the temperature of point P the center of the control volume as in Fig. (2) at time t+Δt can be calculate in term of temperature at time t in the adjacent points.

$$\mathbf{a_p T^1_p = a_e T^\circ_e + a_w T^\circ_w + (a_p - a_e - a_w) T^\circ_p} \qquad (2)$$

Where

$$\mathbf{a_p = \frac{(\rho C)_t \Delta x}{\Delta t}} \quad , \quad \mathbf{(\rho C)_t = [\phi(\rho C)_f + (1-\phi)(\rho C)_s]}$$

$$\mathbf{a_e = \frac{K_e}{(\delta x)_e}} \quad , \quad \mathbf{a_w = \frac{K_e}{(\delta x)_w}}$$

For the outside surface of the porous wall as shown in Fig. (1), the discretization equation of energy balance:

$$\mathbf{a_1 T_1^1 = [a_1 - a_a - a_R - a_2] T_1^\circ + a_a T_a^\circ + a_R T_g^\circ + a_2 T_2^\circ + b} \qquad (3)$$

Where

$$\mathbf{a_1 = \frac{(\rho C)_t \Delta x}{\Delta t}} \quad , \quad \mathbf{a_a = h_a} \quad , \quad \mathbf{a_2 = \frac{K_e}{\Delta x}}$$

$$\mathbf{a_R = \frac{\sigma (T_1^{\circ 2} + T_g^{\circ 2})(T_1^\circ + T_g^\circ)}{1/\varepsilon_g + 1/\varepsilon_w - 1}} \quad , \quad \mathbf{b = \tau_g \alpha_w I}$$

For the inside surface of the wall shown in Fig. (1), the discretization equation of energy balance can be written as:

$$\mathbf{a_N T_N^1 = [a_N - a_{N-1} - a_1 - a_R] T_N^\circ + a_{N-1} T_{N-1}^\circ + a_1 T_r^\circ + a_R T_r^\circ} \qquad (4)$$

Where

$$\mathbf{a_N = \frac{(\rho C)_t \Delta x}{\Delta t}} \quad , \quad \mathbf{a_{N-1} = \frac{K_e}{\Delta x}}$$

$$\mathbf{a_1 = h_i} \quad , \quad \mathbf{a_R = \sigma \varepsilon_w (T_N^{\circ 2} + T_r^{\circ 2})(T_N^\circ + T_r^\circ)}$$

The discretization equation for the glass layer can be written as follows:

$$\mathbf{a_g T_g^1 = [a_g - a_\circ - a_{Ro} - a_a - a_{Rw}] T_g^\circ + a_\circ T_\circ^\circ + a_{Ro} T_{sky}^\circ + a_a T_A^\circ + b} \qquad (5)$$

Where

$$a_g = \rho_g C_g \frac{\Delta g}{\Delta t} \quad , \quad a_o = h_o$$

$$a_a = h_a \quad , \quad a_{Ro} = \sigma \varepsilon_g (T_g^{\circ 2} + T_{sky}^{\circ 2})(T_g^{\circ} + T_{sky}^{\circ})$$

$$a_{Rw} = h_{Rw} = \frac{\sigma (T_g^{\circ 2} + T_1^{\circ 2})(T_g^{\circ} + T_1^{\circ})}{1/\varepsilon_g + 1/\varepsilon_w - 1} \quad , \quad b = [\alpha_g + \tau_g (1-\alpha_w)]I$$

The average air temperature in the gap T_a can be computed from the energy balance on air in the gap (Akbarzadeh 1982):

$$T_a = T_{in} + \left(\frac{2T_{in} - T_1 - T_g}{2}\right) \times \left[-\frac{\dot{m}C_a}{2h_a A_P}\left(\exp - \left\{\frac{2h_a A_p}{\dot{m}C_a}\right\} - 1\right) - 1\right] \tag{6}$$

And the exit air temperature from the air gap can be computed from the following equation :

$$T_{out} = T_{in} + \left(\frac{2T_{in} - T_1 - T_g}{2}\right) \times \left(\exp - \left\{\frac{2h_a A_p}{\dot{m}C_a}\right\} - 1\right) \tag{7}$$

It is necessary to estimate the air mass flow rate $(\dot{m})$. The mass flow rate can be calculated by the following equation:

$$\dot{m} = \rho_a \overline{V} A_V \tag{8}$$

The mean air velocity in the gap $(\overline{V})$ has been estimated (Duffie 1980) by a solution of Bernoulli's equation. This based on the assumption that density and air temperature in the gap vary linearly with height of the wall $(\overline{H})$. So the average velocity through the gap can be determined from the following equation (Akbarzadeh 1982):

$$\overline{V} = \sqrt{\frac{2g\overline{H}}{C_1\left(\frac{A_p}{A_V}\right)^2 + C_2} \times \frac{T_m - T_r}{T_m}} \tag{9}$$

Where T_m is the mean air temperature in the gap=T_a

The wall layers are divided to strips, each strip equal to 1 cm (Δx=0.01m). The time step is equal to 100 s to satisfy the criteria of stability (Patanker 1980). The discretization equations (2-5) are solved for each time step. Hour by hour calculation for a period of heating for three months (Dec.1999 to Feb2000) under Baghdad climatic conditions.

The heat transfer to the room for vented thermal storage porous wall is calculated from the following equation:

$$\mathbf{Q} = \mathbf{Q_C} + \mathbf{Q_R} + \mathbf{Q_{CR}} \tag{10}$$

Where Q_C and Q_R are heat flux due to convection and radiation respectively:

$$\mathbf{Q_C} = \mathbf{h_i}\left(\mathbf{T_N} - \mathbf{T_r}\right) \tag{11}$$

$$\mathbf{Q_R} = \sigma\varepsilon_w\left(\mathbf{T_N^4} - \mathbf{T_r^4}\right) \tag{12}$$

The rate of heat flux that enters the room due to air circulation (Q_{CR}) can be computed as:

$$\mathbf{Q_{CR}} = \frac{\dot{m}\mathbf{C_a}}{\mathbf{A_p}}\left(\mathbf{T_{out}} - \mathbf{T_{in}}\right) \tag{13}$$

The rate of heat per unit area stored in the wall (Q_{SR}) can be calculated from:

$$\mathbf{Q_{SR}} = \tau_g \mathbf{I} - \frac{\sigma\left(\mathbf{T_1^4} - \mathbf{T_g^4}\right)}{1/\varepsilon_w + 1/\varepsilon_g - 1} - \mathbf{h_a}\left(\mathbf{T_1} - \mathbf{T_a}\right) - \mathbf{Q} \tag{14}$$

RESULTS AND DISCUSSION

The results of the mathematical model that is derived in the previous section will be presented and discussed. The hourly variation for solar intensity on the south facing vertical wall and ambient temperature data are taking from the solar energy research center, Jaderia-Baghdad.the porous wall having dimension equal to 2.8m height and 2.5m width, 0.04 vent area to the wall area ratio. The air gap width equal to 0.1 m. the solar intensity for clear and cloudy day on the wall is shown in Fig. (3). The 9^{th} and 26^{th} February was chosen to represent the cloud and clear days respectively in this study. Fig. (4) and (5) show the hourly variation of the rate of heat flux transferred to the living space “room” during a selected clear and cloudy day. The living space assumed to be at a constant temperature equal to 20 ºC. The hourly variation of the rate heat flux studied for the following cases:

1. Vented porous wall without night insulation (VPORWN).
2. Unvented porous wall without night insulation (NVPORWN).
3. Vented Concrete wall without night insulation (VCONWN).
4. Unvented Concrete wall without night insulation (NVCONWN).

For clear day Fig. (4), for Concrete wall, there is a positive heat flux to the room during the day. But for unvented wall the heat flux due to heat conduction through the wall starts to increase at (9 A.M.) till it reach the maximum value at (5 P.M.) which have the value equal to 192 W/m². While for a vented wall system, the heat flux is due to conduction through the wall in addition to thermo-circulation, so it start rising from (8 A.M.) till (3 P.M.) where its maximum value is about 225 W/m². So in the case of vented system there is about 23% increase in heat gain through the heat period over that of unvented system. It is therefore evident that wall with natural air circulation construction is only useful when immediate heat transfer, i.e. without delay required.

For wall that is constructed from porous material (gravel), its behavior is the same as that of Concrete wall .but its values of heat flux are relatively small than the Concrete wall. For unvented wall the heat starts to increase in (9 A.M.) and reach its maximum value at (5 P.M.) and its value equal to 177 W/m². And for vented wall start to increase at (8 A.M.) and reach the maximum value at (3 P.M.) which equal to 210 W/m². So there is an increase for vented system to unvented one by a 20%. And the Concrete wall is 7% higher than porous wall in transferring heat flux, this is because the porous wall having specific heat value greater than that for Concrete wall, so the porous wall having the ability to store the heat instead of transfer the heat to the living space.

For cloudy day, Fig. (5) illustrates the hourly variation of heat flux coming into the room. For all compared systems, there is a negative heat flux transfer to the room during most of the day hours. This is means that there is a heat loss from the room to the ambient. So it causes more auxiliary heat required during cloudy whether to compensate the energy loss. There is a positive value of heat flux coming to the room at the beginning of the day, i.e. in the morning hours, from (0 A.M.) to (7 A.M.) hour for unvented systems (Concrete and porous wall), this is because the heat store in the wall from the last day discharged to the room in the beginning of the present day. And to (10 A.M.) for vented systems, this is due to additional heat from the thermo-circulation which delays the negative value of heat flux. The Concrete wall appears a relatively increase in heat flux coming to the room than that of porous wall.

The rate of heat storage in the wall is equal the difference between heat received by the wall from the sun and heat transfer out of the wall from both side by convection, radiation and by thermo-circulation for vented wall system. The storage heat depends mainly on the material and thickness of the wall. So three different thicknesses for porous wall of 0.1m, 0.15m and 0.2m are compared with 0.2m thickness of Concrete wall,

Figs. (6) to (7) illustrate the variation of heat stored in the walls for different thicknesses for vented and for clear and cloudy day. Fig.(6) shows the hourly variation of heat stored through different wall systems, for clear day with walls having vents, Fig. (6) shows that Concrete with thickness 0.2m having approximately the same behavior and the values of heat stored in porous wall with thickness 0.1m. For other porous wall thicknesses, the heat stored in 0.15m is a 3-9% greater than porous wall with thickness 0.1m and Concrete wall with thickness 0.2m. The wall which having a thickness of 0.2m is 8-15% greater than that of porous wall with 0.1m thickness and Concrete wall with thickness 0.2m. This is because the specific heat for gravel is greater than that for Concrete. The behavior of storage heat is the same for all systems. The wall starts to be charged with heat. I.e. becomes positive at about (7 A.M.) for all system except that for 0.2m porous wall which starts to charges at (6 A.M.). The system still charged until reach the maximum value at (2 P.M.) which equal to 470 W/m² for porous wall with thickness 0.2m. and then begin to discharge heat to the ambient through the sunset until reach the minus value.

CONCLUSIONS

1. The heat flux that enters the room for concrete wall is greater than that in the case of using a porous wall.
2. The heat stored in the case of porous wall is greater than that of concrete wall.
3. The heat stored in the wall increases with increasing thickness of the porous wall.

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NUMENCLATURES:

A	Area (m^2)
A_P	Projected area (m^2)
A_V	Vent area (m^2)
C	Specific heat (J/kg.K)
g	Acceleration of gravity (m/s^2)
H	Wall height (m)

$\bar{H} = H_m$	Distance between vents (m)
h	Heat transfer coefficient (W/m².K)
I	Solar intensity (W/m²)
K	Thermal conductivity (W/m.K)
L	Wall thickness (Air mass flow rate in the gap (kg/s)
Q_C	Rate of heat flux due to convection (W/m²)
Q_{CR}	Rate of heat flux due to thermo circulation (W/m²)
Q_R	Rate of heat flux due to radiation (W/m²)
Q_{SR}	Rate of heat stored in the wall (W/m²)
q	Rate of heat flux (W/m²)
T	Temperature (K)
T°	Temperature at time t (K)
T^1	Temperature at time t+Δt (K)
T_m	Mean air temperature in the gap (K)
$\bar{V}$	Mean air velocity in the gap (m/s)
w	Width of the wall (m)
x,y	Coordinates

GREEK SYMBOLS

α	Absorbtivity
ρ	Density (kg/m³)
ϕ	Porosity
ε	Emmisivity
σ	Stefan-Boltzman constant (W/m².K^4)
τ	Transmissivity

SUBSCRIPTS

A	Air
Cond	Conduction
Conv	Convection
f	Fluid
g	Glass
i	Inside
in	Inlet
N	Inside wall face
o	Outside
out	Outlet
P	Center point
r	Room
rad	Radiation
s	Solid
v	vent
w	Wall
1	outside wall face

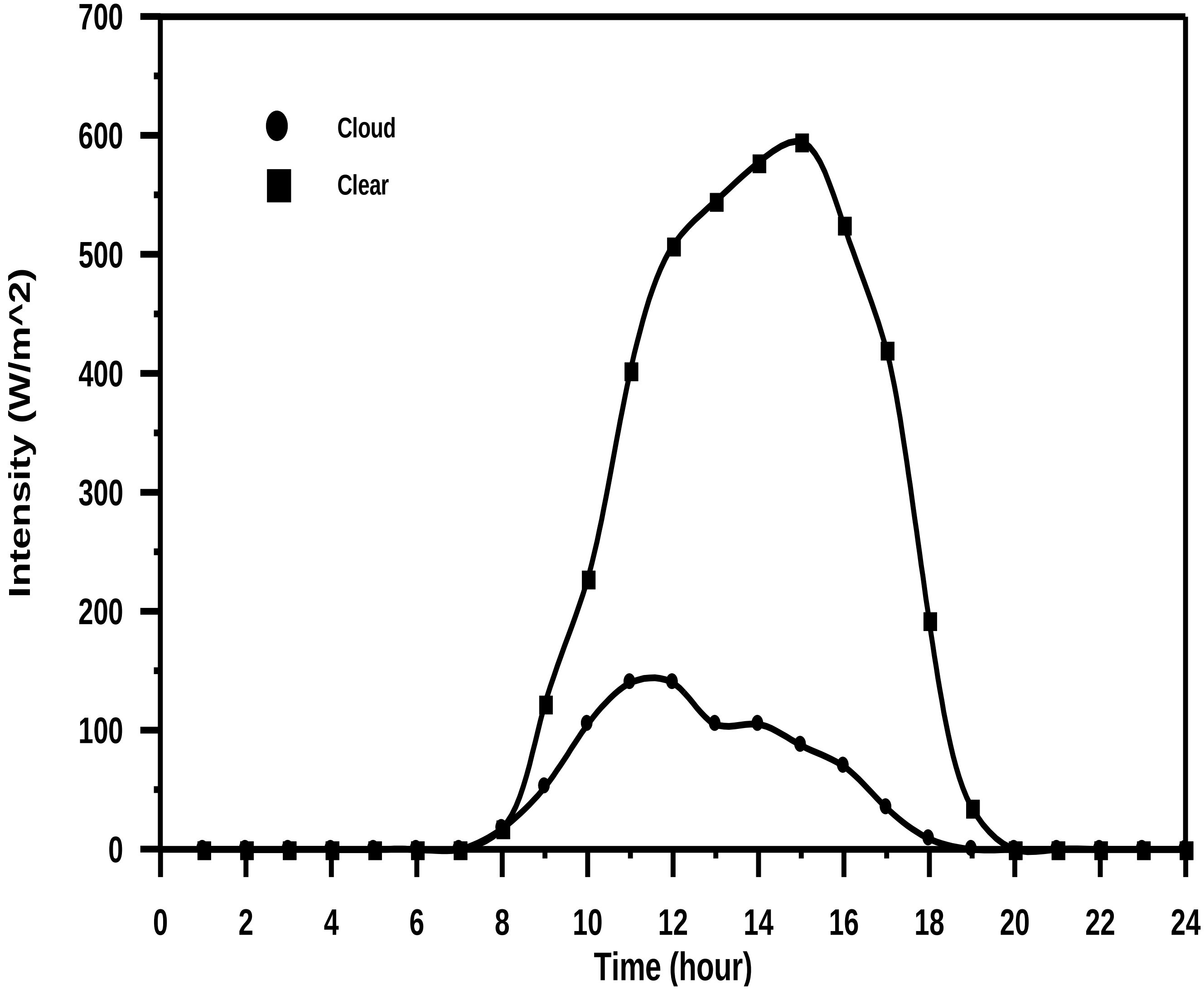

Fig. 3. Solar intensity on wall for clear and cloudy day.

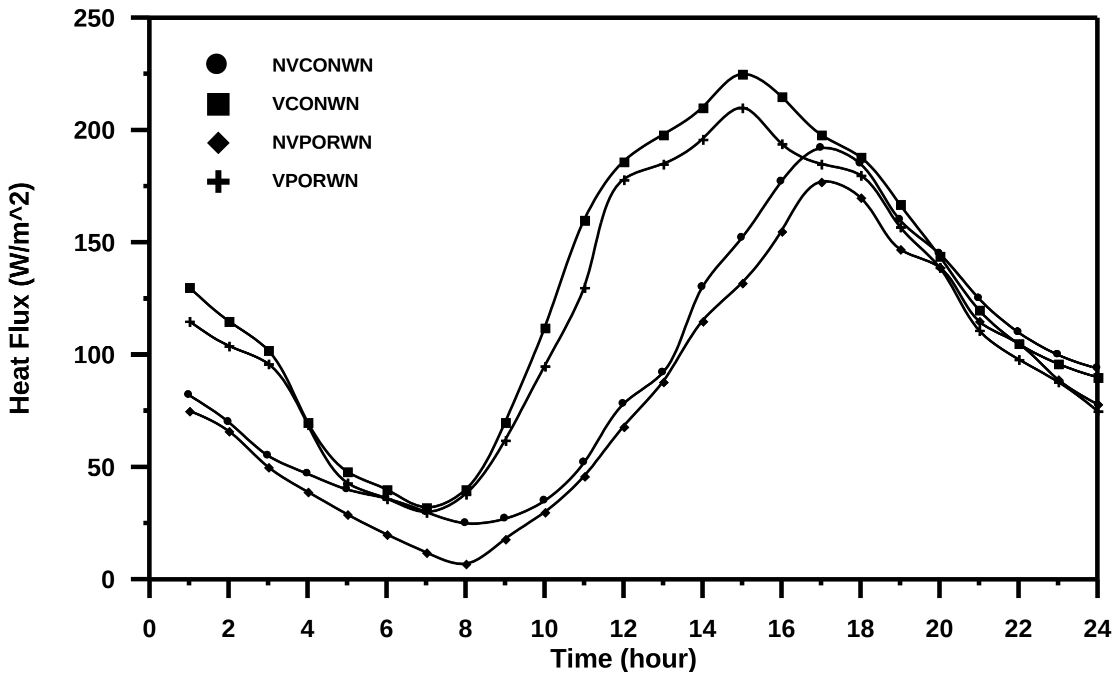

Fig. 4. Heat flux for Concrete and porous wall without night insulation (clear day).

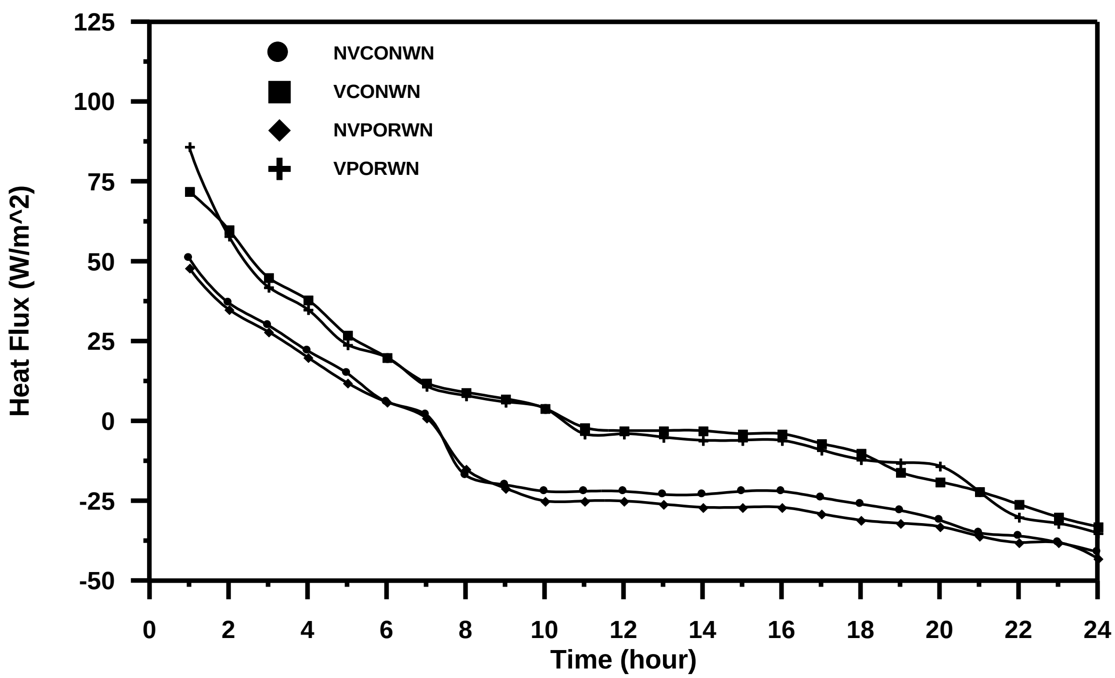

Fig. 5. Heat flux for Concrete and porous wall without night insulation (cloud day).

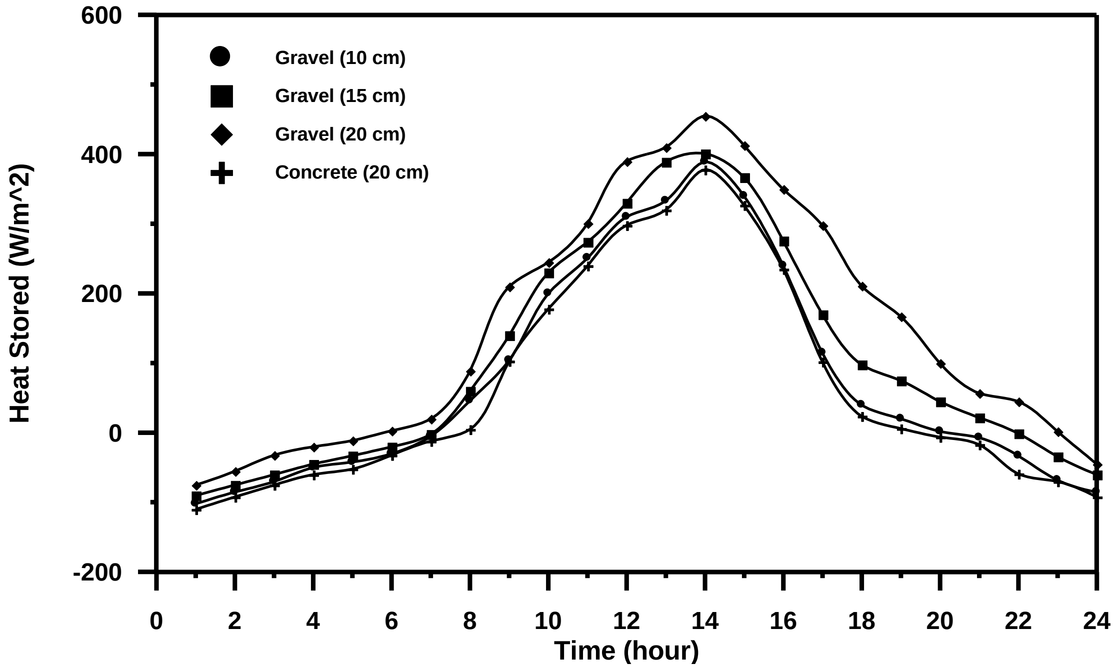

Fig. 6. Comparison between Concrete wall and different thicknesses porous wall heat stored with vents (clear day).

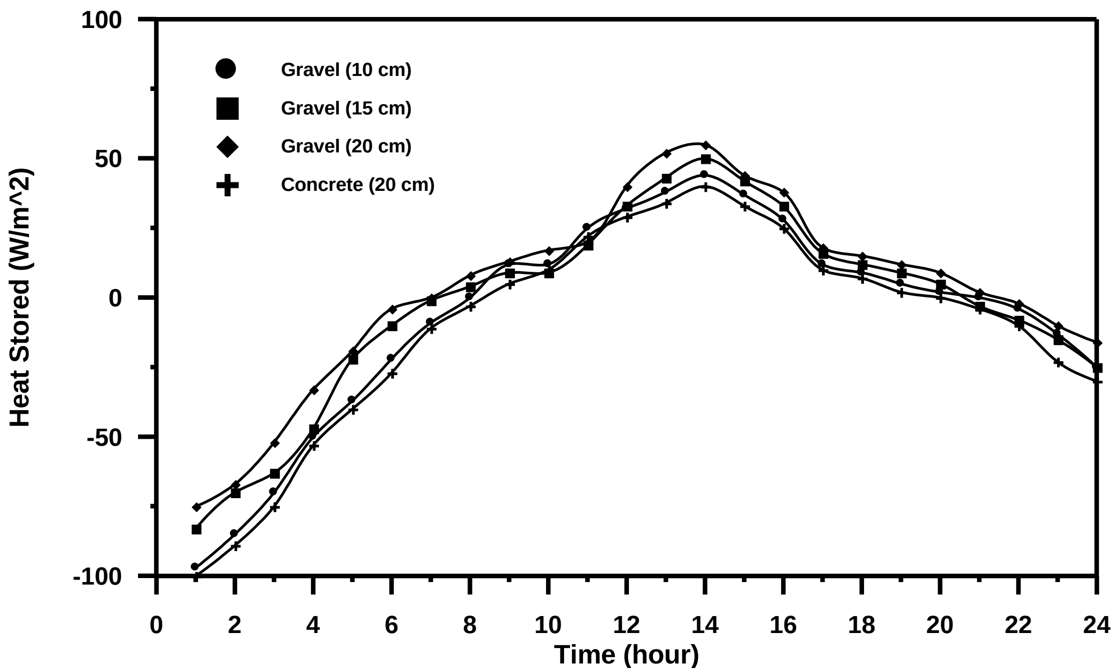

Fig. 7. Comparison between Concrete wall and different thicknesses porous wall heat stored with vents (cloud day).