2852

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Evaluation of Complex Heat Transfer Coefficients for Passive Heating Concepts

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Passive heating concepts namely Trombe wall, Water wall and Trans wall have been analysed to obtain overall heat transfer coefficients for average values and for time-dependent variations. The numerical values have been obtained and tabulated for various wall thicknesses.

NOMENCLATURE

- A area (m^2)
- A_0 constant (°C)
- a_0 average solair temperature (°C)
- A_1 constant (°C/m)
- a_n *n*th harmonic in the Fourier expansion of solair temperature (°C)
- A_{w1} area of first water column (m^2)
- A_{w2} area of second water column (m^2)
- C specific heat (J/Kg °C)
- C_a specific heat of air (J/Kg °C)
- C_w specific heat of water (J/Kg °C)
- d_{w1} width of first water column facing glazing (m)
- d_{w2} width of second water column facing the room (m)
- h_0 heat transfer coefficient from front surface of the wall to ambient (W/m^2 °C)
- h_1 heat transfer coefficient from blackened surface of the wall to the enclosed air (W/m^2 °C)
- h'_1 heat transfer coefficient from blackened surface of plate to water (W/m^2 °C)
- h_2 heat transfer coefficient from enclosed air to glazing (W/m^2 °C)
- h'_2 heat transfer coefficient from water to the concrete layer (W/m^2 °C)
- h_3 heat transfer coefficient from glazing to ambient (W/m^2 °C)
- h_4 heat transfer coefficient from interior surface of the wall to the room (W/m^2 °C)
- h_r radiative heat transfer coefficient from blackened surface of the wall to the glazing (W/m^2 °C)
- h_R heat transfer coefficient from concrete wall to room in the case of water wall (W/m^2 °C)
- h_{t1} heat transfer coefficient from front surface of the trap to first water column (W/m^2 °C)
- h_{t2} heat transfer coefficient from trap to second water column (W/m^2 °C)
- h_{wa} heat transfer coefficient from first water column to the ambient (W/m^2 °C)
- K thermal conductivity (W/mk)
- L thickness of the wall and trap material (m)
- M_{w1} mass of water in first water column (kg)
- M_{w2} mass of water in second water column (kg)
- $\dot{m}_a$ mass flow rate of air (kg/sec)
- n number of harmonics (integer)
- r reflectance (dimensionless)
- S_0 average solar insolation (W/m^2)
- S_n *n*th harmonic of solar insolation in its Fourier series expansion (W/m^2)
- T temperature of the wall and the trap (°C)
- t time (sec)
- T_a ambient temperature (°C)
- T_{a0} average value of ambient temperature (°C)
- T_{an} *n*th harmonic in the Fourier series expansion of ambient temperature (°C)
- T_R room temperature (°C)
- T_{sa} solair temperature (°C)
- T_{w1} temperature of first water column (°C)
- T_{w2} temperature of second water column (°C)
- X coordinate (m)
- ω $2\pi/T$
- λ_n constant (°C)
- λ'_n constant (°C)
- τ_g transmittance of glazing (dimensionless)
- α_g absorptance of the blackened surface of the wall (dimensionless)
- ρ density (Kg/m^3)
- $(E_{bj}-E_{bj-1})/E_b$ emissive power of a black body source with $E_{b0}=0$ and $E_{bn}=E_b$ (dimensionless)
- λ wavelength (μm)
- μ_j extinction coefficient of trap material for solar radiation in the wavelength region between j and $j-1$
- ν_j fractional absorption of solar radiation in water in the wavelength region between j and $j-1$ (dimensionless)
- η_j extinction coefficient of water for solar radiation in the wavelength region between j and $j-1$.
- σ_n phase of the *n*th harmonic of heat transfer coefficient (radians)

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1. INTRODUCTION

PASSIVE heating concepts for building have been a subject of several studies in recent years [1–6]. Using numerical simulation analysis [7,8], the year long performance of storage walls has been well characterized. Simple empirical methods [9,10] have also been presented for estimating the annual solar heating performance of a building using either thermal storage wall or direct gain concept.

The periodic technique based on Fourier series representation of temperature and heat flux has been extensively applied [11,12] to rate solar passive heating concepts. This rating has often been expressed in terms of the heat flux coming into a room assumed to be maintained at a constant temperature. In this approach each time either the geometry or the location of the building changes, one has to perform a fresh set of detailed numerical calculations. In this paper, the passive heating concepts, namely Trombe wall with or without vents, Water wall and Trans wall, have been characterized in terms of overall complex heat transfer coefficients, appropriate for periodic variations. The heat transfer coefficients, which are independent of the meteorological parameters and the area of the wall, can be used to quickly evaluate the effect of passive concepts on building response; the heat flux in an air-conditioned room (with constant temperature of room air) can be expressed as a simple function on these coefficients and Fourier coefficients of the solair temperature at the outer interface of the wall. For some concepts in which the heat collection and the subsequent heat transfer mechanism is different than an opaque wall, an equivalent solair temperature has to be redefined to take advantage of the overall definition of heat transfer coefficient for the calculation of heat flux.

2. ANALYSIS

2.1. *Trombe wall without vents*

Corresponding to the configuration given in Fig. 1a, the heat transfer through the glazed mass wall can be assumed to be one dimensional governed by the following heat conduction equation, the periodic solution of which is written as

$$T(x,t) = A_0 + A_1 x + R_e \sum_{n=1}^{\infty} (\lambda_n e^{\beta_n x} + \lambda_n' e^{-\beta_n x}) e^{in\omega t}, \quad (1)$$

where

$$\beta_n = (1+i)\left\{\frac{n\omega\rho c}{2K}\right\}^{1/2}. \quad (2)$$

The unknown constants A_0, A_1, λ_n and λ_n' are to be determined by the application of appropriate boundary conditions which can be written as

$$-K\frac{\partial T}{\partial x}\bigg|_{x=0} = h_0[T_{sa} - T(x,t)|_{x=0}] \quad (3)$$

and

$$-K\frac{\partial T}{\partial x}\bigg|_{x=L} = h_4[T(x,t)|_{x=L} - T_R]. \quad (4)$$

In equation (3), the solair temperature is an equivalent environmental temperature which takes into account the mechanism of radiation absorption and subsequent heat transfer from the hot surface.

The right hand side in equation (4) represents the heat flux, $\dot{Q}$, coming into the room. Substituting for T from equation (1) in equations (3) and (4) and solving the resultant algebraic equations one obtains the expressions for the unknown constants and the heat flux. The expression for the heat flux, $\dot{Q}$, can be expressed in the form

$$\dot{Q} = U_0(a_0 - T_R) + R_e \sum_{n=1}^{\infty} U_n a_n e^{in\omega t}, \quad (5)$$

where a_0 and a_n are Fourier coefficients of the time variation of solair temperature, i.e.,

$$T_{sa} = a_0 + R_e \sum_{n=1}^{\infty} a_n e^{in\omega t} \quad (6)$$

and U_0 and U_n defined as the average overall heat transfer coefficients and the complex heat transfer coefficient for the harmonic are given by the expressions.

$$U_0 = \left[\frac{1}{h_0} + \frac{L}{K} + \frac{1}{h_4}\right]^{-1} \quad (7)$$

and

$$U_n = \frac{Kh_0h_4\beta_n}{[(h_0h_4 + K^2\beta_n^2)\sinh(\beta_n L) + (h_0 + h_4)K\beta_n\cosh(\beta_n L)]}, \quad (8)$$

The overall heat transfer coefficient from the collecting

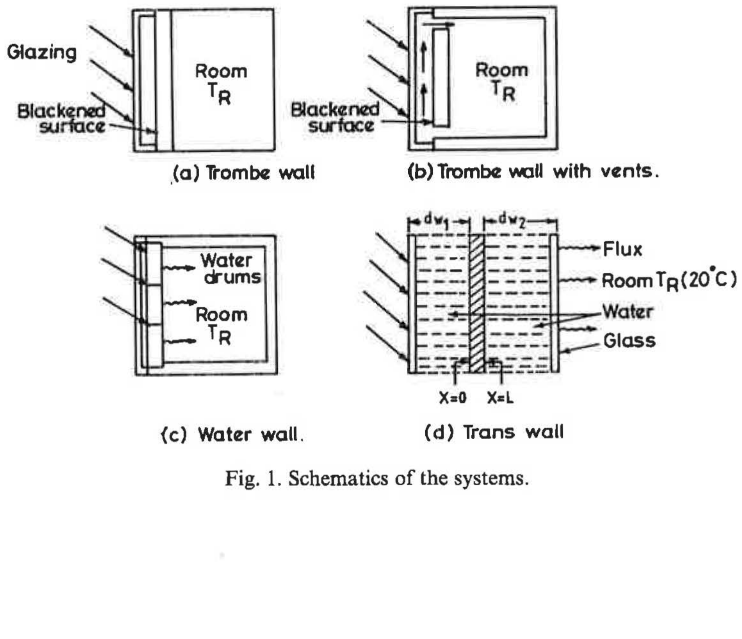

Fig. 1. Schematics of the systems.

surface to the ambient is in equation (7). In fact, this again consists of 3 parts, *viz* the conductance of the air gap between the hot surface and the glazing, the conduction effect of the glazing and the heat loss from the outermost surface of the glazing. As with a flat plate collector, an overall heat transfer coefficient is assigned to single or double glazed surfaces [11,12].

2.2. *Trombe wall with vents*

For Trombe wall with vents (Fig. 1b), the heat transfer from the hot surface consists of two parts (i) heat losses to the ambient through glazing and (ii) heat transfer to the moving air in the air gap, in addition to heat conduction through the wall. The heat flux, therefore, into the room consists of two parts i.e.

$$\dot{Q} = \dot{Q}_k + \dot{Q}_c, \tag{9}$$

where

$$\dot{Q}_k = h_R[T(x,t)|_{x=L} - T_R] \tag{10}$$

and

$$\dot{Q}_c = \frac{\dot{m}_a c_a}{A}[\theta_{\text{out}} - T_R]. \tag{11}$$

θ_{out} is the temperature of hot air, entering the room through the upper vent. After rearrangement, the expression for heat flux can be put in the form,

$$\dot{Q} = U_0[G_1(G_2S_0 + T_{a0}) - T_R] + R_e \sum_{n=1}^{\infty} U_n(G_nS_n + T_{an})e^{in\omega t}. \tag{12}$$

As with equation (5), U_0 and U_n may be termed as overall average and associated nth harmonic heat transfer coefficients respectively, and $G_1(G_2S_0 + T_{a0})$ and $(G_nS_n + T_{an})$ as the modified solair temperatures, expressions for various parameters being given in Appendix A.

2.3. *Water wall*

The water wall consists of water filled in drums as the storage media (Fig. 1c). The water wall may have a concrete structure at its back surface facing the room. Following the analysis given in Nayak *et al.* [11], the expression for the heat flux, when there is no concrete wall, can be written in the same form as equation (5) with,

$$U_0 = \left[\frac{1}{h_0} + \frac{1}{h'_1} + \frac{1}{h_4}\right]^{-1} \tag{13}$$

and

$$U_n = \left[\frac{h_0 h'_1 h_4}{h_0 h'_1 + h_0 h_4 + h'_1 h_4 + (h'_1 + h_4)(M_w C_w in\omega/A)}\right]. \tag{14}$$

In equation (13) h_0 is the overall heat transfer coefficient from the heat collection surface to the ambient, h'_n is the coefficient of heat transfer from hot surface to water and h_4 is the overall heat transfer coefficient from water to the room air.

If the water wall is followed by a thin concrete wall, U_0 and U_n assume the following expressions

$$U_0 = \left[\frac{1}{h_0} + \frac{1}{h'_1} + \frac{1}{h'_4} + \frac{L}{K} + \frac{1}{h_R}\right]^{-1} \tag{15}$$

and

$$U_n = h_R[F_1 e^{\beta_n L} + F_2 e^{-\beta_n L}]. \tag{16}$$

In equation (15) h'_4 is the heat transfer coefficient from water to the concrete surface in contact with water, where F_1 and F_2 are given in Appendix B.

2.4. *Trans wall*

Trans wall, a translucent storage wall introduced by Fuchs and McClelland [9] and shown conceptually in Fig. 1d, has been studied earlier by Sodha *et al.* [13]. Since solar radiation is absorbed throughout the translucent media, the governing heat conduction equation for the temperature distribution is

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{K}\frac{\partial T}{\partial x} = \rho c \frac{\partial T}{\partial t} \tag{17}$$

where $I(x,t)$, the solar intensity at any point inside the translucent material is given by the expression [14],

$$I(x,t) = \tau_g(1-r)S(t)\sum_{j=1}^{5}\frac{E_{bj} - E_{bj-1}}{E_b}e^{-\mu_j x}, \tag{18}$$

with $I(x,t)$ given by equation (18), the solution of equation (18) is obtained as,

$$T(x,t) = A_0 + A_1 x - \frac{S_0\tau_g(1-s)}{K}\sum_{j=1}^{5}\frac{E_{bj}-E_{bj-1}}{\mu_j E_b} \times e^{-\mu_j x}\nu_j e^{-\eta_j d_{w1}} + R_e\sum_{n=1}^{\infty}\left\{\lambda_n e^{\beta_n x} + \lambda'_n e^{-\beta_n x} - \frac{S_n\tau_g(1-s)}{K}\sum_{j=1}^{5}\frac{\mu_j}{\mu_j^2 - \beta_n^2}\frac{E_{bj}-E_{bj-1}}{E_b} \cdot \nu_j e^{-\eta_j d\omega_1}\cdot e^{-\mu_j x}\right\}e^{in\omega t}. \tag{19}$$

With appropriate boundary conditions given as

$$K\frac{\partial T}{\partial x}\bigg|_{x=0} = h_{t1}[T(x,t)|_{x=0} - T_{w1}(t)], \tag{20}$$

$$-K\frac{\partial T}{\partial x}\bigg|_{x=L} = h_{t2}[T(x,t)|_{x=L} - T_{w2}(t)], \tag{21}$$

$$\frac{M_{w1}C_\omega}{A_{\omega 1}}\frac{\partial T_{w1}}{\partial t} = h_{t1}[T(x,t)|_{x=0} - T_{w1}(t)] + \tau_g(1-s)S(t)\left\{1 - \sum_{j=1}^{5}\nu_j e^{-\eta_j d_{w1}}\right\} - h_{wa}[T_{w1}(t) - T_a(t)] \tag{22}$$

and

$$\frac{M_{w2}C_\omega}{A_{w2}}\frac{\partial T_{w2}}{\partial t} = h_{t2}[T(x,t)|_{x=L} - T_{w2}(t)] + \tau_g(1-s)S(t)\sum_{j=1}^{5}\nu_j e^{-\eta_j d_{w1}}\{1 - \nu_j e^{-\eta_j d_{w2}}\} \cdot \frac{E_{bj}-E_{bj-1}}{E_b}e^{-\mu_j L} - h_4[T_{w2}(t) - T_R]. \tag{23}$$

Table 1. Values of different heat transfer coefficients (HTC) and thermophysical parameters

	HTC (W/m^3 °C)	Specific heat (J/kg °C)	K (W/m K)	Density (kg/m^3)	Other	
h_0	6.0				$\dot{m}_a$	0.104 kg/sec
h_1	3.2				s	0.04
h'_1	206.5				T_R	20°C
h_2	2.9				τ_g	0.9
h'_2	206.5				α_g	0.9
h_3	21.96					
h_4	8.29					
h_r	4.9					
h_R	8.29					
h_{t1}	200					
h_{t2}	200					
h_{wa}	6.0					
Concrete		795.5	0.72	1858		
Trap		1500	0.2	1190		
Air		1008				
Water		4200				

After involved but simple algebra, the flux entering into the room can be expressed in the form,

$$\dot{Q} = h_4 S'[G'_1(G'_2 S_0 + T_{a0}) - T_R] + h_4 h_{wa} S''[G'_n S_n - T_{an}] \tag{24}$$

where $h_4 S' (= U_0)$ and $h_4 h_{wa} S'' (= U_n)$ are the overall average and nth harmonic complex heat transfer coefficients and the equivalent solair temperatures for Trans wall have the following Fourier coefficients

$$a_0 = G'_1(G'_2 S_0 + T_{a0})$$

$$a_n = (G'_n S_n - T_{an})$$

The expressions for G_1, G_2, G_n, S' and S'' are given in Appendix C.

3. RESULTS AND DISCUSSIONS

Various values of heat transfer coefficients and thermophysical properties of the materials used in the calculation of overall heat transfer coefficients are given in Table 1. The values of extinction coefficients and absorption coefficients for Transwall are given in Table 2.

With these values of the wall properties, the numerical values of the average and other harmonic for overall heat-transfer coefficients for various passive heating concepts discussed in this paper are given in Tables 3–7. The nth harmonic heat transfer coefficient U_n is complex as $U_n = A_n \exp(i\sigma_n)$, A_n and σ_n being given in the tables. On the average, the overall U-value for the Trombe wall with vents is higher than other passive components i.e. Trombe wall without vents, Water wall and Trans wall. Also there is little change in its value with increasing wall thickness for the case of vents, essentially because the convective heat transfer starts dominating and the phase lag attenuation goes on reducing as the wall thickness increases.

Average heat flux into a room of constant temperature environment depends on the equivalent average solair temperature and the overall heat transfer coefficient. These are given in Tables 8 and 9 for different heat capacities. On average it is seen that though the solair temperature for the water wall and Trombe wall is identical, the water wall has larger U-value. This results in the transfer of greater heat flux into the room.

Looking only at the average values, the Trombe wall with vents gives the best performance; however the time-dependent behaviour shows that the storage capacity of this type of Trombe wall is negligible. The time-dependent behaviour of the heat flux (a measure of the overall performance) is shown in Figs 2 and 3 corresponding to the solair temperature variations for Trombe wall, Water wall and Trans wall given in Figs 4 and 5. It is observed that the solair for the Trombe wall without vents and the water wall has maximum amplitude; this, along with the appropriate damping effect of various harmonics of heat transfer coefficients, yields positive flux for the water wall throughout 24 hr.

Table 2. Value of extinction and absorption coefficients in trap (translucent) material for solar radiation in different wavelength regions

Wavelength region	$E_{bj} - E_{bj-1}/E_b$	μ	ν	η
$0 \leqslant \lambda \leqslant 0.36$	0.08137	0.0	0.237	0.032
$0.36 \leqslant \lambda \leqslant 1.06$	0.66880	0.725	0.193	0.450
$1.06 \leqslant \lambda \leqslant 1.3$	0.08620	3.82	0.167	3.00
$1.3 \leqslant \lambda \leqslant 1.6$	0.06120	9.45	0.179	35.0
$1.6 \leqslant \lambda \leqslant 0.0$	0.10244	0.0	0.224	255.0

Table 3. Amplitude and phase of the heat transfer coefficient of Trombe wall without vent

$L(m)$		n = 0	1	2	3	4	5	6
0.10	A_n	2.35	1.88	1.202	0.82	0.596	0.453	0.356
	σ_n	0	5.4502	4.8701	4.4914	4.2034	3.9633	3.7528
0.15	σ_n	2.02	1.191	0.613	0.37	0.244	0.17	0.123
		0	4.9225	4.2186	3.7359	3.3433	3.0033	2.6997
0.20	σ_n	1.77	0.74	0.326	0.174	0.103	0.065	0.426
		0	4.4600	3.6116	2.9925	2.4814	2.0380	1.6417
0.25	σ_n	1.58	0.47	0.177	0.083	0.043	0.025	0.015
		0	4.02730	3.0043	2.2448	1.6176	1.0724	0.5843
0.30	σ_n	1.42	0.3034	0.0959	0.039	0.018	0.0094	0.00513
		0	3.5999	2.3939	1.4968	0.75416	0.10721	5.8100

Table 4. Trombe wall with vents ($\dot{m}/A = 0.104$ kg/sec)

$L(m)$		n = 0	1	2	3	4	5	6
0.05	A_n	4.65	4.49	3.982	3.50	3.14	2.88	2.70
	σ_n	0	6.0885	5.9606	5.9031	5.8907	5.9016	5.9229
0.10	A_n	4.51	3.8048	3.014	2.64	2.48	2.39	2.36
	σ_n	0	5.9686	5.9287	5.9775	6.0328	6.0783	6.1131
0.15	A_n	4.43	3.24	2.65	2.497	2.456	2.445	2.441
	σ_n	0	5.9535	6.0265	6.1005	6.1445	6.1686	6.1817
0.20	A_n	4.35	2.9264	2.5985	2.5521	2.5385	2.5238	2.5055
	σ_n	0	6.0059	6.1115	6.1592	6.1760	6.1812	6.1827
0.25	A_n	4.30	2.805	2.648	2.62	2.586	2.55	2.517
	σ_n	0	6.0683	6.1538	6.172	6.1741	6.1742	6.1751

Table 5. Water wall without a concrete slab

M_w (kg)		n = 0	1	2	3	4	5	6
50	A_n	3.41	2.316	1.431	1.004	0.768	0.620	0.520
	σ_n	0	5.45779	5.14478	5.01088	4.93918	4.89494	4.86503
100	A_n	3.41	1.431	0.7678	0.5192	0.3914	0.3138	0.2620
	σ_n	0	5.14478	4.93918	4.86503	4.82726	4.80443	4.78915
150	A_n	3.41	1.0042	0.519	0.348	0.2619	0.2097	0.175
	σ_n	0	5.9088	4.86503	4.81469	4.78915	4.77384	4.76362
200	A_n	3.41	0.7678	0.3914	0.2619	0.1966	0.1574	0.131
	σ_n	0	4.9392	4.8272	4.7892	4.7700	4.7585	4.7508
250	A_n	3.41	0.620	0.314	0.209	0.157	0.126	0.105
	σ_n	0	4.8949	4.80443	4.7738	4.7585	4.74929	4.74315

Table 6. Water wall with a concrete layer of thickness 0.1 m

M_w (kg)		n = 0	1	2	3	4	5	6
50	A_n	2.26	0.8678	0.4114	0.2380	0.1519	0.1033	0.0735
	σ_n	0	4.68986	4.10009	3.69385	3.37274	3.10431	2.87136
100	A_n	2.26	0.5382	0.2391	0.1338	0.0836	0.0560	0.03944
	σ_n	0	4.49300	3.9524	3.5660	3.2590	3.0021	2.7784
150	A_n	2.26	0.3853	0.1675	0.0927	0.05748	0.0383	0.2689
	σ_n	0	4.4060	3.8925	3.5163	3.2161	2.9642	2.7444
200	A_n	2.26	0.2990	0.1286	0.0708	0.0437	0.0291	0.0204
	σ_n	0	4.3578	3.8603	3.49004	3.19364	2.9445	2.72687
250	A_n	2.26	0.24404	0.1044	0.0573	0.0353	0.02345	0.01642
	σ_n	0	4.3272	3.8402	3.4738	3.1798	2.9325	2.7161

Table 7. Amplitude and phase of the heat transfer coefficient of trans wall with $M_{w1} = M_{w2} = 100$ kg and $d_{w1} = d_{w2} = 0.1$ m

L(m)		n = 0	1	2	3	4	5	6
0.005	A_n	3.1	0.639	0.262	0.138	0.0845	0.0564	0.0401
	σ_n	0	1.3507	0.9169	0.6747	0.5234	0.4212	0.3478
0.01	A_n	2.87	0.517	0.1824	0.089	0.0521	0.034	0.024
	σ_n	0	1.1338	0.6686	0.4469	0.3173	0.2304	0.1665
0.02	A_n	2.51	0.352	0.107	0.0497	0.0283	0.0182	0.0126
	σ_n	0	0.8585	0.4010	0.1901	0.0575	6.2398	6.1559
0.03	A_n	2.23	0.2569	0.074	0.033	0.0186	0.0117	0.008
	σ_n	0	0.6751	0.2046	6.2479	6.0754	5.9320	5.8046
0.04	A_n	2.01	0.198	0.0542	0.0239	0.013	0.00798	0.0053
	σ_n	0	0.5216	0.00857	5.9972	5.7681	5.5705	5.3931
0.05	A_n	1.82	0.158	0.0416	0.0177	0.0093	0.0054	0.0035
	σ_n	0	0.3750	6.0800	5.7174	5.4266	5.1757	4.9525

4. CONCLUSIONS

Explicit expressions for the average overall heat transfer coefficients and the associated complex heat transfer coefficients for various harmonics have been obtained for the Trombe wall, Water wall and Trans wall passive heating concepts. The performance of buildings incorporating any of these can be easily evaluated by using the values of overall heat transfer coefficients tabulated in this paper. The expressions for an equivalent solair temperature for the Trombe wall with vents, Trans wall and Water wall are also obtained in the process.

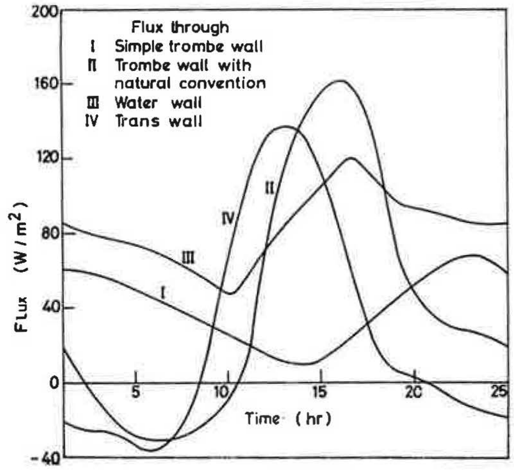

Fig. 3. Hourly variations of the flux entering into the room through different systems for heat capacity equal to 443.2 kJ/°C.

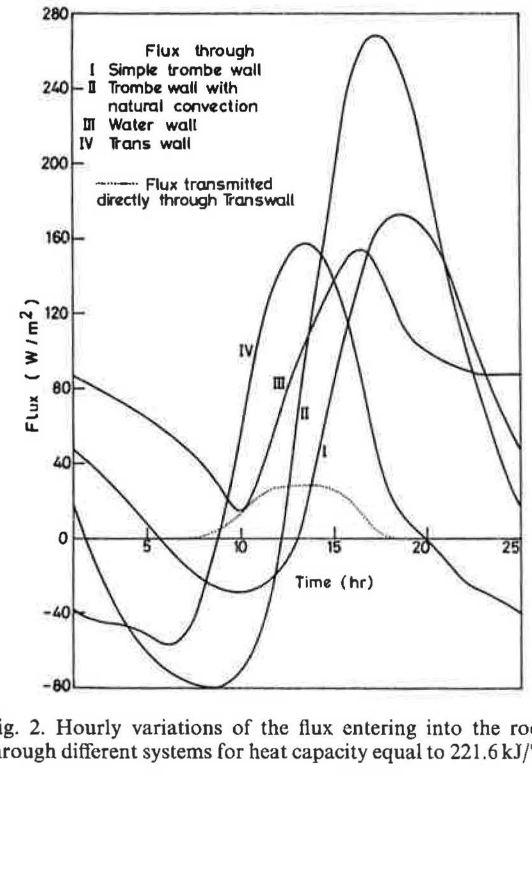

Fig. 2. Hourly variations of the flux entering into the room through different systems for heat capacity equal to 221.6 kJ/°C.

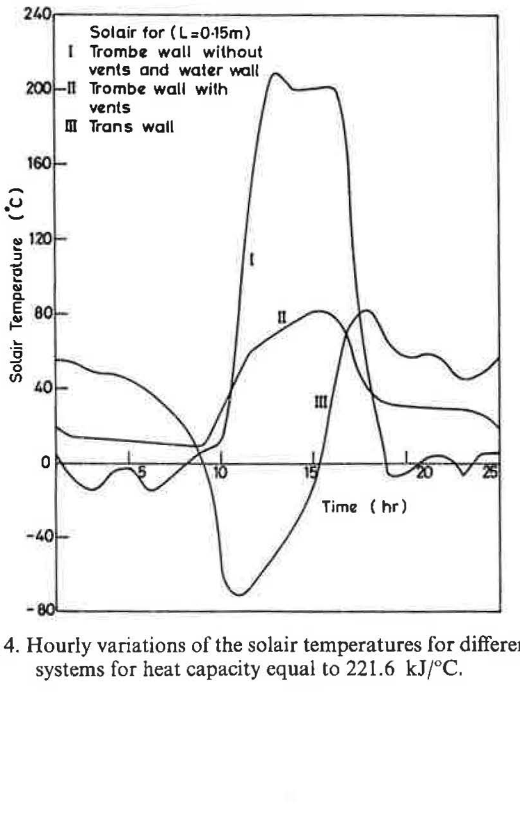

Fig. 4. Hourly variations of the solair temperatures for different systems for heat capacity equal to 221.6 kJ/°C.

Table 8. Average solair, heat transfer coefficients and flux for different passive heating concepts for different heat capacities (kJ/°C)

Total heat capacity (M_PC_p/m²) of the wall (kJ/°C)	Trombe wall without vents			Trombe wall with vents (natural convection)			Water wall			Trans wall		
	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)
221.6	2.02	44.4	49.3	4.43	33.0	57.6	3.42	44.4	83.45	1.82	30.0	18.2
443.2	1.42	44.4	34.6	4.26	31.8	50.2	3.42	44.4	83.45	1.82	33.0	23.7
664.8	1.10	44.4	26.8	4.17	30.7	44.6	3.42	44.4	83.45	1.82	34.0	25.5

Table 9. Average solair, heat transfer coefficients and flux for different passive heating concepts for different wall thicknesses

Total thickness of the wall (L) (m)	Trombe wall without vents			Trombe wall with vents			Water wall			Trans wall*		
	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)	U_0 (W/m² °C)	T_{s0} (°C)	Q_0 (W/m²)
0.15	2.02	44.4	49.3	4.43	33.0	57.6	3.42	44.4	83.45	1.82	30.0	23.7
0.30	1.42	44.4	34.6	4.26	31.8	50.2	3.42	44.4	83.45	1.82	34.0	25.5
0.45	1.10	44.4	26.8	4.17	30.7	44.6	3.42	44.4	83.45	1.82	35.3	28.0

* (I) $d_{w1} = 0.1$ m; $d_{w2} = 0.0$ m; trap thickness = 0.05 m. (II) $d_{w1} = 0.15$ m; $d_{w2} = 0.10$ m; trap thickness = 0.05. (III) $d_{w1} = 0.3$ m; $d_{w2} = 0.10$ m; trap thickness = 0.05 m.

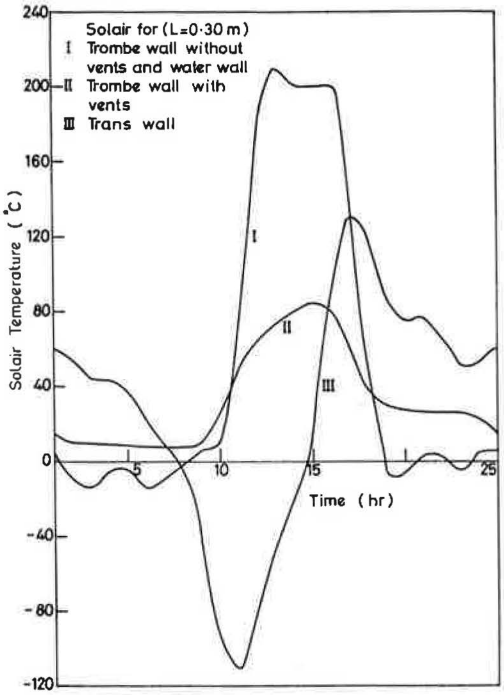

Fig. 5. Hourly variations of the solair temperature for different systems for heat capacity equal to 443.2 kJ/°C.

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APPENDIX A

$$U_0 = h_4 P_{12} P_{14} - P_{17} \quad \text{(A1)}$$

$$G_1 = (P_{19} + h_4 P_{12} P_{14} P_{16})/U_0 \quad \text{(A2)}$$

$$G_2 = (P_{10} + P_{12} P_{14} P_{15} h_4)/(P_{19} + P_{12} P_{14} P_{16}) \quad \text{(A3)}$$

$$U_n = Z_{11} + h_4(Z_n\, e^{\beta_n L} + Z_7\, e^{-\beta_n L} \quad \text{(A4)}$$

$$G_n = [Z_{10} + h_4(Z_0\, e^{\beta_n L} + Z_6\, e^{-\beta_n L})]/U_n \quad \text{(A5)}$$

$$P_{19} = W(S_2 - S_1 P_{11} P_{13}) \quad \text{(A6)}$$

$$P_{18} = -S_1 W P_{10} P_{13} \quad \text{(A7)}$$

$$P_{17} = W[S_3 + S_1(1 - P_{12} P_{13})] \quad \text{(A8)}$$

$$P_{16} = -P_{11}/P_{12} \quad \text{(A9)}$$

$$P_{15} = -P_{10}/P_{12} \quad \text{(A10)}$$

$$P_{14} = K/h_4 \quad \text{(A11)}$$

$$P_{13} = L + \frac{K}{h_4} \quad \text{(A12)}$$

$$P_{12} = -h_4(P_9 - P_7)/H \quad \text{(A13)}$$

$$P_{11} = -h_4 P_8/H \quad \text{(A14)}$$

$$P_{10} = -h_4 \alpha_g \tau_g/H \quad \text{(A15)}$$

$$P_9 = P_6(h_1 + h_\gamma P_2) \quad \text{(A16)}$$

$$P_8 = h_1 P_5 + h_\gamma(P_3 + P_2 P_5) \quad \text{(A17)}$$

$$P_6 = \frac{W}{1 - Gh_2 P_2} \quad \text{(A18)}$$

$$P_5 = \frac{Gh_2 P_3}{1 - Gh_2 P_2} \quad \text{(A19)}$$

$$P_4 = \frac{G(h_1 + h_2 P_1)}{1 - Gh_2 P_2} \quad \text{(A20)}$$

$$P_3 = \frac{h_3}{h_2 + h_3 + h_\gamma} \quad \text{(A21)}$$

$$P_2 = \frac{h_2}{h_2 + h_3 + h_\gamma} \quad \text{(A22)}$$

$$P_1 = \frac{h_\gamma}{h_2 + h_3 + h_\gamma} \quad \text{(A23)}$$

$$H = h_4 K + P_7(K + h_4 L) \quad \text{(A24)}$$

$$S_1 = h_1 + h_2 P_1 + h_2 P_2 P_4 \quad \text{(A25)}$$

$$S_2 = h_2(P_2 P_5 + P_3) \quad \text{(A26)}$$

$$S_3 = h_2(P_2 P_6 - 1) - h_1 \quad \text{(A27)}$$

$$G = \frac{1 - W}{h_1 + h_2} \quad \text{(A28)}$$

$$W = \frac{m_a C_a}{A(h_1 + h_2)} \left[1 - \exp\left\{ \frac{-(h_1 + h_2)A}{\dot{m}_a C_a} \right\} \right] \quad \text{(A29)}$$

$$Z_{11} = W(Z_6 + Z_8) \quad \text{(A30)}$$

$$Z_{10} = WS_1(Z_7 + Z_9) + S_2 W \quad \text{(A31)}$$

$$Z_9 = -\frac{Z_4 Z_7}{Z_3} \quad \text{(A32)}$$

$$Z_8 = -\frac{Z_4 Z_6}{Z_3} \quad \text{(A33)}$$

$$Z_7 = \frac{Z_3 P_8}{Z_5} \quad \text{(A34)}$$

$$Z_6 = \frac{Z_3 \tau_g \alpha_g}{Z_5} \quad \text{(A35)}$$

$$Z_5 = Z_2 Z_3 - Z_1 Z_4 \quad \text{(A36)}$$

$$Z_4 = (h_4 - K\beta_n)\, e^{-\beta_n L} \quad \text{(A37)}$$

$$Z_3 = (h_4 + K\beta_n)\, e^{\beta_n L} \quad \text{(A38)}$$

$$Z_2 = (P_7 + K\beta_n) \quad \text{(A39)}$$

$$Z_1 = (P_7 - K\beta_n) \quad \text{(A40)}$$

APPENDIX B

$$h_e = \left(\frac{1}{h_0} + \frac{1}{h_1} \right)^{-1} \quad \text{(B1)}$$

$$R_1 = \frac{h_2}{h_e + h_2 + M_w C_w in\omega} \quad \text{(B2)}$$

$$R_2 = \frac{h_e}{h_e + h_2 + M_w C_w in\omega} \quad \text{(B3)}$$

$$R_3 = h_2 - K\beta_n \quad \text{(B4)}$$

$$R_4 = h_2 + K\beta_n \quad \text{(B5)}$$

$$R_5 = (h_2 - K\beta_n) - \left[\frac{h_2^2}{h_e + h_2 + M_w C_w in\omega} \right] \quad \text{(B6)}$$

$$R_6 = (h_2 + K\beta_n) - \left[\frac{h_2^2}{h_e + h_2 + M_w C_w in\omega} \right] \quad \text{(B7)}$$

$$R_7 = \frac{h_e h_2}{h_e + h_2 + M_w C_w in\omega} \quad \text{(B8)}$$

$$R_8 = (h_R + K\beta_n)\, e^{\beta_n L} \quad \text{(B9)}$$

$$R_9 = (h_R - K\beta_n)\, e^{-\beta_n L} \quad \text{(B10)}$$

$$R_{10} = (h_R + K\beta_n)\, e^{\beta_n L} R_6 - (h_R - K\beta_n)\, e^{-\beta_n L} R_5 \quad \text{(B11)}$$

$$F_1 = \frac{R_7 R_9}{R_{10}} \quad \text{(B12)}$$

$$F_2 = \frac{R_7 R_8}{R_{10}} \quad \text{(B13)}$$

APPENDIX C

$$S' = S_{15}$$

$$G'_1 = S_{13}/S_{15}$$

$$G'_2 = E_9/S_{13}$$

$$S'' = y_{36}$$

$$G'_n = \frac{S_1 EE(J)}{S'' h_{wa}}$$

$$S_1 = \tau(1-\gamma)/K$$

$$S_2 = \frac{\tau}{h_4}$$

$$S_3 = \frac{h_{t2}}{h_8}$$

$$S_4 = \frac{\tau(1-\gamma) h_{t2}}{K \cdot h_8}$$

$$S_5 = \frac{\tau(1-\gamma)}{h_8}$$

$$S_6 = \frac{h_4}{h_8}$$

$$S_7 = S_3 h_{10}$$

$$S_8 = \frac{(h_{t1} - B_6)}{B_2}$$

$$S_9 = (h_{t1} + S_8 h_{t2})$$

$$S_{10} = K - S_8 h_5$$

$$S_{11} = S_9 h_{10} + S_{10} S_7$$

$$S_{12} = S_{10} S_6$$

$$S_{13} = \frac{S_{11}}{B_{11}}$$

$$S_{14} = \frac{S_{12}}{B_{11}}$$

$$S_{15} = 1 + S_{14}$$

$$SS = \tau(1-\gamma)$$

$$h_5 = h_{t2} L + K$$

$$h_6 = h_{t1} + h_{wa}$$

$$h_7 = h_{t2} + h_4$$

$$h_8 = h_{t2} L$$

$$h_9 = \frac{h_6}{h_{t1}}$$

$$E_1 = \sum_{j=1}^{5} \frac{E_{bj} - E_{bj-1}}{\mu_j E_b} e^{-\mu_j L} \nu_j e^{-\eta_j d_{w1}}$$

$$E_2 = \sum_{j=1}^{5} \frac{E_{bj} - E_{bj-1}}{E_b} e^{-\mu_j L} \nu_j e^{-\eta_j d_{w1}}$$

$$E_3 = \sum_{j=1}^{5} \frac{E_{bj}-E_{bj-1}}{E_b} e^{-\mu_j L} v_j^2 e^{-\eta_j \cdot (d_{w1}+d_{w2})}$$

$$E_4 = \sum_{j=1}^{5} \frac{E_{bj}-E_{bj-1}}{\mu_j E_b} v_j e^{-\eta_j \cdot d_{w1}}$$

$$E_5 = \sum_{j=1}^{5} v_j e^{-\eta_j d_{w1}}$$

$$E_6 = \frac{\tau_g}{h_8}\left[\frac{(1-s)h_2 E_1}{K} + (1-s)(E_2-E_3) - \frac{(1-s)h_{t2} t_4}{K} + \frac{h_{t2}(1-E_5)}{h_{t1}}\right]$$

$$E_7 = \sum_{j=1}^{5} \left(\frac{E_{bj}-E_{bj-1}}{E_b}\right) v_j e^{-\eta_j \cdot d_{w1}}$$

$$E_8 = S_1 h_{t1} E_4 + SSE_7 + S_1 S_8 h_{t2} E_1 - S_8 SSE_2 + S_{10} E_6 - S_9 S_1 E_4 + S_9 S_2 - S_9 S_2 E_5$$

$$E_9 = \frac{E_8}{B_8}$$

$$EE(J) = \sum_{j=1}^{5} \frac{\mu_j}{\mu_j^2 - \beta_n^2} \cdot \frac{E_{bj}-E_{bj-1}}{E_b} \cdot v_j e^{-\eta_j \cdot d_{w1}} \cdot \left\{ e^{-\mu_j L}\left[\frac{h_{t2}}{K}(1+y_{37}) - \mu_j y_{37} + \frac{h_{t1}}{K} \times (y_{36}+y_{38}) + \mu_j y_{38}\right\} - (1 - v_j e^{-\eta_j d_{w2}}) \times \left\{ y_{36} + y_{35} \cdot \frac{E_{bj}-E_{bj-1}}{E_b} e^{-\mu_j L} v_j e^{-\eta_j d_{w1}} \right\}.$$

$$B_1 = \frac{h_7}{h_8}$$

$$B_2 = \frac{h_{t2} h_9}{h_8}$$

$$B_3 = h_{t2} h_9 - h_5 B_2$$

$$B_4 = h_5 B_1 - h_{t2}$$

$$B_5 = \frac{B_4}{B_3}$$

$$B_6 = h_{t1} h_9 + K B_2$$

$$B_7 = h_{t1} B_5 - K B_1$$

$$B_8 = B_7 - B_6 B_5$$

$$Y_1 = h_{t1} - K\alpha_n$$

$$Y_2 = h_{t1} + K\alpha_n$$

$$Y_3 = (h_{t2} + K\alpha_n)\exp(\alpha_n L)$$

$$Y_4 = (h_{t2} + K\alpha_n)\exp(-\alpha_n L)$$

$$Y_5 = h_{t1} + h_{wa} + \frac{m_{w1} C_w in\omega}{A_{w1}}$$

$$Y_6 = h_{t2}\exp(\alpha_n L)$$

$$Y_7 = h_{t2}\exp(-\alpha_n L)$$

$$Y_8 = h_{t2} + h_4 + \frac{in\omega C_w m_{w2}}{A_{w2}}$$

$$Y_9 = y_4 - \frac{y_2 y_3}{y_1}$$

$$Y_{10} = \frac{h_{t1} y_3}{y_1 y_9}$$

$$Y_{11} = h_{t1}\left(1 - \frac{y_2}{y_1}\right)$$

$$Y_{12} = \frac{h_{t1}^2}{y_1}$$

$$Y_{13} = y_{12} - y_5$$

$$Y_{14} = \frac{y_{11}}{y_9}$$

$$Y_{15} = \frac{y_3 y_{11}}{y_1 y_9}$$

$$Y_{16} = y_{10} y_{11}$$

$$Y_{17} = \frac{y_2 y_{11}}{y_9}$$

$$Y_{18} = y_{13} - y_{16}$$

$$Y_{19} = \frac{y_{14}}{y_{18}}$$

$$Y_{20} = \frac{y_{15} - (h_{t1}/y_1)}{y_{18}}$$

$$Y_{21} = \frac{y_{17}}{y_{18}}$$

$$Y_{22} = \frac{1}{y_{18}}$$

$$Y_{23} = y_7 - \frac{y_6 y_2}{y_1}$$

$$Y_{24} = \frac{h_{t1} y_6}{y_1}$$

$$Y_{25} = y_{24} - y_{10} y_{23}$$

$$Y_{26} = \frac{y_{23} h_{t2}}{y_9} - y_8$$

$$Y_{27} = \frac{y_6}{y_1}$$

$$Y_{28} = \frac{y_3 y_{23}}{y_1 y_9}$$

$$Y_{29} = \frac{y_{23}}{y_9}$$

$$Y_{30} = y_{28} - y_{27}$$

$$Y_{31} = y_{26} - y_{21} y_{25}$$

$$Y_{32} = -y_{22} y_{25}$$

$$Y_{33} = y_{19} y_{25} - y_{29}$$

$$Y_{34} = y_{30} - y_{20} y_{25}$$

$$Y_{35} = \frac{1}{y_{31}}$$

$$Y_{36} = \frac{y_{32}}{y_{31}}$$

$$Y_{37} = \frac{y_{33}}{y_{31}}$$

$$Y_{38} = \frac{y_{34}}{y_{31}}$$