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Effect of an Absorptive Coating on Solar Energy Storage in a Thrombe wall system

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Abstract

An analysis is undertaken to show the effects of a range of coating absorptivity values on the improvement of heat transfer across a Trombe wall (which is used for passive solar heating) and to its enclosure. The analysis shows that enhanced heat delivery to the enclosure of a Trombe wall system is feasible with the application of an absorptive coating of a superior nature – characterized by high absorptivity and very low emissivity – on the heat-receiving surface of the wall and thus can be seen as a heat transfer enhancement technique.

Keywords: Coating; Solar; Thrombe

1. Introduction

The efficiency of heat exchange in Thrombe walls depends to a reasonable extent on the geometric characteristics (surface of exchange) and thermal behaviour (parameters which could influence thermal diffusivity). Analysis of the absorption potential could be based on the following criteria:

- Maximization of the energy stored and dissipated for a given geometry and period based on a certain wall thickness.
- Maximization of power delivery to the enclosure which is of the form:

$$P = h_{av} A \Delta T \qquad (1)$$

where h_{av} is the average coefficient of heat transfer which accounts for the variation in the convective heat transfer coefficient in the enclosure; A the exposed area of the wall; ΔT is the temperature difference between the interior surface of the wall and the enclosure. The task is to evaluate and maximize the absorption potential of a Thrombe wall system relying on the absorptive property of the exterior wall coating so as to improve heat dissipation to the enclosure during solar radiation outage (i.e. nocturnal period).

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2. Problem formulation

Consider the absorptive area of a Thrombe wall of height b (m), width c (m) and thickness L (m) facing towards the sun and in combination with the east, west and north walls form an enclosure for passive heating. The dimensions of the wall satisfy the following:

$$b \approx c, \quad b \gg L, \quad \text{and} \quad c \gg L$$

assuming that

- The exchange of heat to the enclosure is through the wall and the convection vents.
- The wall is coated on the exterior with a film of solar absorptivity, α_c and of negligible emissivity.
- The parameters ρ, c, k are constant for the circulating mass of air.
- The enclosure consists of isothermal vertical surfaces and the top and bottom surfaces are perfectly insulated.

3. Heat absorption and storage analysis

The formulation of transient heat conduction tasks in the Thrombe wall involves the change in energy content with time. Modelization of the conduction problem in the system is commonly obtained by numerical formulation. At the start of a

Nomenclature

A	Thrombe wall Surface Area (m^2)
Gr	Grashof Number
h	Convective Heat Transfer Coefficient (W/m^2 K)
i	Time Step
k	Thermal Conductivity (W/m K)
M	Number of Nodes
n	Node (0, 1, 2, ...)
Nu	Nusselt Number
Pr	Prandtl Number
q	Average Solar Heat Flux (W/m^2)
Q	Heat Transfer Rate (W)
Ra	Raleigh Number
t	Time (s)
T	Absolute Temperature (K)
x	Co-ordinate x
Δx	Mesh Fourier Number

Greek symbols

α	Thermal diffusivity (m^2/s)
α_c	Absorptivity
ε	Emissivity
ι	Transmissivity
ρ	Density (kg/m^3)
σ	Stefan–Boltzmann Constant (W/m^2 K)
χ	Reflectivity

Subscripts

av	Average
c	Solar Absorptivity of Coating
comb	Combined
in	Inside
out	Outside
tw	Thrombe wall

Superscripts

i	Time Step
Ω	Total Number of Time Intervals

day, typically, the inner surface temperature of the Thrombe wall falls until solar energy absorbed by the exterior diffuses through the wall.

The equation of conservation of heat flux is written as:

$$h_{out}[T_{out} - T(L,t)] + h_{in}[T_{in} - T(0,t)] + \iota\alpha_c q^i(t) + kA\frac{\partial[T(x,t) - T(0,t)]}{\partial x}\bigg|_{x=L} = \rho CL\frac{\partial T(x,t)}{\partial t}\bigg|_{x=L} \quad (2)$$

After discretization and using the explicit method, with M (0, 1, ..., $n-1$, n) number of nodes and general temporal step i, Eq. (2) for node 0 (Fig. 1) reduces to:

$$T_0^{i+1} = \left(1 - 2\tau - \frac{2\tau h_{in}\Delta x}{k}\right)T_0^i + 2\tau T_1^i + \frac{2\tau h_{in}\Delta x T_{in}^i}{k} \quad (3)$$

The convection heat transfer coefficient for the enclosure is computed from the correlation of Berkovsky and Polevikov recommended in [1] for an enclosure consisting of two isothermal surfaces of different temperatures and spaced at a distance δ apart:

$$\overline{Nu}_\delta = 0.18\left(\frac{Pr}{0.2 + Pr}Ra_\delta\right)^{0.29} \quad (4)$$

subject to the following constraints

$$1 < \frac{b}{\delta} < 2, \quad 10^{-3} < Pr < 10^5, \quad \text{and} \quad 10^3 < \frac{Ra_\delta Pr}{0.2 + Pr}$$

where

$$h_{in} = \frac{\overline{Nu}_\delta k}{\delta}$$

The convective heat transfer coefficient can be calculated for the enclosure with slightly different condition [2]:

$$\overline{Nu}_\delta = 0.22\left(\frac{b}{\delta}\right)^{-1/4}\left(\frac{Pr}{0.2 + Pr}Ra_\delta\right)^{0.28} \quad (5)$$

for the following constraints:

$$2 < \frac{L}{\delta} < 10, \quad Pr < 10, \quad \text{and} \quad Ra_\delta < 10$$

The enclosure with isothermal vertical surfaces at T_1 and T_2 and spaced at a distance δ apart and of length b typifies a passive heating system for the Thrombe wall under consideration. A representative value of the heat transfer coefficient at the interior of the wall can be computed to allow for slight variation in the vertical surfaces temperatures during solar radiation outage.

The computerization process of the progress of change of energy content at different points across the wall at varying time calls for discretization, and for any interior node using the explicit method, we have [3]:

$$\begin{aligned} T_1^{i+1} &= \tau(T_0^i + T_2^i) + (1 - 2\tau)T_i \\ &\vdots \\ T_n^{i+1} &= \tau(T_{n-2}^i + T_n^i) + (1 - 2\tau)T_{n-1}^i \end{aligned} \quad (6)$$

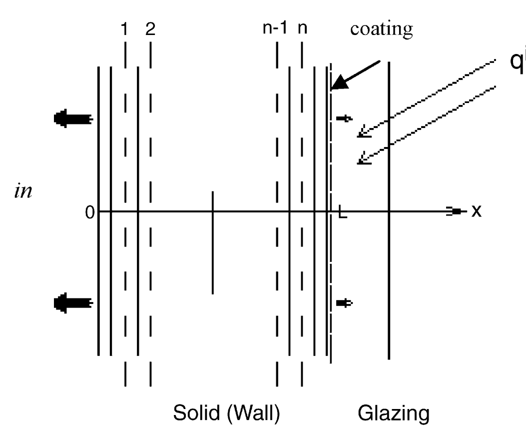

Fig. 1. Physical Model and Nomenclature of the Wall.

where

$$\tau = \frac{\alpha_c \Delta t}{\Delta x^2}$$

The exterior node of the wall is contiguous to the air space bordered by a plastic (or a glazing) envelope. The explicit finite difference formulation for the node, n, is written as:

$$h_{out}(T^i_{out} - T^i_n) + \iota \alpha_c A q^i - \frac{\varepsilon_c \varepsilon_p \sigma (T_c^4 - T_p^4)}{1 - \chi_c \chi_p} = \rho A C \left(\frac{\Delta x}{2}\right) \frac{T^{i+1}_n - T^i_n}{\Delta t} \quad (7)$$

where the term $\varepsilon_c \varepsilon_p (T_c^4 - T_p^4)/(1 - \chi_c \chi_p)$ is the net radiation between the opaque coated surface (subscripted with c) and the partially transparent plastic (subscripted with p) [4]. The symbols ε, χ, T represent emissivity, reflectivity and absolute temperature, respectively. The net radiation term is insignificant for an excellent absorptive coating of low emittance quality and for very small temperature difference between the exterior node and the envelope. However, if heat transfer from radiative and convective contributions is to be reasonably represented in the balance for the exterior node, for convenience, we include the combined heat transfer coefficient, $h_{out,\ comb}$ that accounts for both effects. A balance for the exterior node of the wall unit can be expressed as:

$$h_{out,comb} A (T^i_{out} - T^i_{in}) + \iota \alpha_c A q^i = \rho C A \left(\frac{\Delta x}{2}\right) \frac{(T^{i+1}_n - T^i_n)}{\Delta t}$$

which simplifies to:

$$T^{i+1}_n = \left(1 - 2\tau - \frac{2\tau h_{out,comb} \Delta x}{k}\right) T^i_n + 2T^i_{n-1} + \frac{2\tau h_{out,comb} T^i_{out} \Delta x}{k} + \frac{2\tau \iota \alpha_c q^i \Delta x}{\Delta t} \quad (8)$$

for stability of the numerical formulation; if

$$\left(1 - 2\tau - \frac{2\tau h_{in} \Delta x}{k}\right) < \left(1 - 2\tau - \frac{2\tau h_{out,comb}}{k}\right)$$

the stability criterion becomes:

$$1 - 2\tau - \frac{2\tau h_{in} \Delta x}{k} \geq 0$$

and consequently

$$\Delta t = \frac{\Delta x^2}{2\alpha_c (1 + (h_{in} \Delta x / k))} \quad (9)$$

The coating absorptivity α_c employed in Eq. (8) represents the amount by which the incident solar radiation on the exterior Thrombe wall surface will be absorbed continuously; and the temperature of the wall would rise with increasing solar radiation. Since unselective coatings are dissipative of the energy which otherwise could be absorbed by the Thrombe wall they may not be ideal for Thrombe wall systems concerned with superior performance. Selective coatings, on the other hand, provide the prospect of increasing the energy storage potential of the system on account of their absorptive vigour, hence we shall rely on the absorptive behaviour of this group of coatings – i.e. coatings with substantial α_c values – to potentially enhance the absorptive (and storage) capacity of the Thrombe wall.

Assuming an absorptive coating is applied to the heat-receiving surface of the wall, the combined heat transfer coefficient $h_{out,\ comb}$ in Eq. (8) could be estimated from the correlation [2]:

$$\overline{Nu}_b = 0.68 Pr^{1/2} \frac{Gr_b^{1/4}}{(0.925 + Pr)^{1/4}} \quad (10)$$

subject to the regime

$$10 < Gr_b Pr < 10^8$$

The problem lies with the determination of the rate of heat transfer from the Thrombe wall to the interior of the enclosure (adjoining node 0) during each temporal step. This is approached by the use of an equation of the form Newton's law of cooling [3]:

$$Q^i_{tw} = h_{in} A \left[\left(\frac{T^i_0 + T^{i-1}_0}{2}\right) - T_{in}\right] \quad (11)$$

Consequently, the amount of heat transfer during each temporal step is computed from the arithmetic average of the temperature at step i and the preceding, $i - 1$. We define the sum total heat transfer rate by the Thrombe wall to the enclosure for Ω time span as:

$$Q_{total} = \sum_{i=1}^{\Omega} Q^i_{tw} \quad (12)$$

Supposing we obtain the number of temporal steps, Eq. (12) will permit the computation of the net heat gain of the enclosure. Assuming T_{in} is maintained constant for a given time range and for steady state condition, we can evaluate the temperature of the outer node T_n for a given time step and for varying α_c values:

$$T^i_n = \left[\frac{\alpha_c q^i + (k/L) T^i_0 + h_{out,comb} T_{air}}{(k/L) + h_{out,comb}}\right] \quad (13)$$

For the analysis, hourly temperature profiles for a Thrombe wall system used for poultry brooding have been obtained and tabulated [5] at the National Center for Energy Research and Development (NCERD), Nsukka, Nigeria. The data distributions on hourly basis include: the interior and exterior surface temperatures, temperature of the brooding room (i.e. the enclosure), temperature of the plastic cover, and temperature of the ambient (inside and outside). The analytical process entails computation of the variation of the innermost node temperature (i.e. at node 0) of the wall relative to varying coating values in addition to different enclosure conditions. The distribution of (computed) temperatures across the wall (nodes 0 through 6) for designated temporal steps have been plotted in Figs. 2–4 for different α_c values. Also, the net amount of heat that would be delivered to the enclosure as a consequence of different coating absorptivity values have been illustrated.

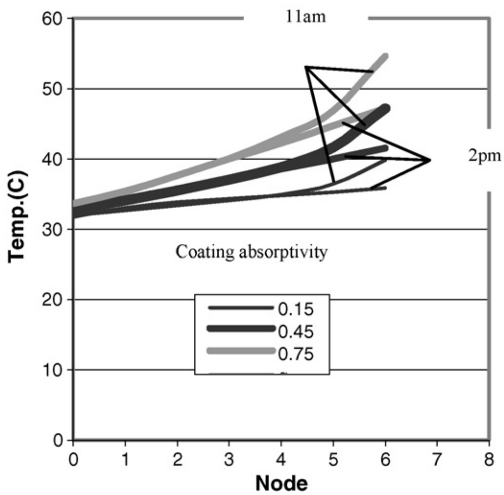

Fig. 2. Temperature profile across the Thrombe wall for time steps corresponding to 11 a.m. and 2 p.m. for varying α_c values for a given day [5].

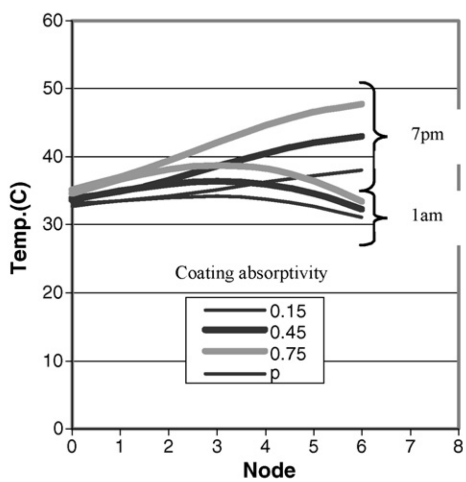

Fig. 3. Temperature profile across the Thrombe wall for time steps corresponding to 7 p.m. and 1 a.m. for varying α_c for a given day [5].

4. Discussion

From an analytical viewpoint, results show improved heat delivery to the enclosure with increasing coating absorptivity values. While there may not be substantial temperature increase at the innermost surface node (node 0) as shown in Figs. 2 and 3, the net heat delivery rate to the enclosure improved with increasing α_c values (Fig. 4). For $\alpha_c = 0.45$, the heat delivered to the enclosure improved by 34% on the average when compared with the heat delivered at $\alpha_c = 0.15$. Likewise, for $\alpha_c = 0.75$, we observe about 44% increase in the heat delivered by the wall to the enclosure when related to the delivery at $\alpha_c = 0.45$, which indicates that higher absorptive coating values can significantly improve heat absorption and transfer across a Thrombe wall; the trend is expected to continue for higher coating values. The gains of improved heat flux for the cases considered could be sustained by further insulation measures during nocturnal period to avoid undesired heat loss from the enclosure to the surrounding, this will ensure that the interior wall temperature

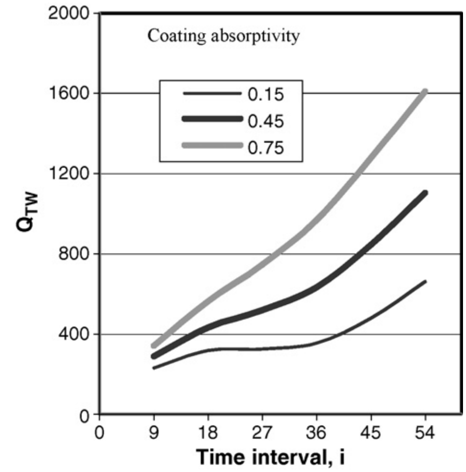

Fig. 4. Relation between the amounts of heat delivered to the enclosure of the Thrombe wall and varying α_c values for a given day [5].

will not reduce considerably therefore impelling a high start-up value the next day. In lieu of some local practices of utilizing coatings which may not have considerable absorptivity in Thrombe wall systems and yet more heat is required per unit time from the sun, we have shown that applying a superior coating with high solar absorptivity we can improve considerably heat delivery to the Thrombe wall enclosure.

5. Conclusion

The absorption and storage capacity of the Thrombe wall can be improved by the application of a coating of superior absorption vigour, and so the practice can be seen as a heat absorption enhancement technique among other alternatives. Optimum application of a heat-absorbing film on the exterior surface of the Thrombe wall will possibly raise the rate of heat delivery to the enclosure. Specific recommendations as to the optimum amount (thickness) to be applied may be examined, or relevant guidelines sourced from the film manufacturer. Also, for every coated surface there is a unit cost to it, this cost may be offset by heat delivery gains to the enclosure overtime. A cost-benefit analysis may be considered to justify any budget on the technique. Expectedly, the predicted values of the interior and exterior nodes temperatures may differ depending on radiation and convection losses within the enclosure system.

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