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Experimental and numerical model of wall like solar heat discharge passive system

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Abstract

The present work raises the use of solar energy as an aid for air conditioning by means of architectural envelope parts such as walls, basically as heat discharge systems. Using a thermal balance applied to these systems, an analytic model was formulated to simulate its behavior and to consider the time variation of the environmental temperature, solar radiation, heat storage in the wall and the temperature of the room to be ventilated. The analytical results were compared against experimental data, creating an experimentally validated model that gives confidence on the accuracy and trustworthiness of the analytic proposal. Six tests were carried out in the experimental model. In four of them, the heat flux simulation was performed with electrical resistors; in the other two, solar radiation was directly employed. The results show that the thermal performance of the system can be appropriately determined and described by the analytical model, within a small margin of error. The proposed analytic model can calculate the behavior of a heat discharge system in walls by simply knowing the dimensions of the prototype and the environmental conditions.

Keywords: Architectural building envelope; Passive cooling; Trombe wall; Natural convection; Solar radiation shield system; Heat discharge

1. Introduction

For a long time man has looked for a way to transform his habitat in order to increase his comfort. However, much of the present architecture does not consider the environment effects properly, and comfort depends on artificial air conditioning. Hence, an economic cost results, as well as an energy and environmental impact. It is then necessary to look for an alternative which will provide man with thermal comfort without using conventional energy, or at least reducing its use substantially. This subject is of major importance in Mexico, where approximately 80% of the energy consumed daily comes from the combustion of hydrocarbons [1].

Several sustainable systems do exist to provide thermal comfort, for example, passive systems (to gain better comfort from advanced knowledge of the relationship between building and environment) and have been given several names: Bioclimatic, Solar, Natural or Ecological Architecture, among others. The present study is about using solar energy as an alternative to reduce or eliminate air conditioning using the architectural envelope as a passive heat discharge system. For this purpose an experimental model was constructed that simulates the thermal performance of such a system applied to walls.

Several studies have already been performed over these systems. Experimentally, Siebers [2], Jaluria [3] and Naylor [4] analyzed the natural convection over a vertical plate and varied the Grashof number between 10^2 and 10^{12}. Hence, they could study the behavior of the phenomenon of natural convection along the length the plate as well as the temperature variation between the working substance and the

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Nomenclature

A	area of the internal plate, m^2
A_I	inlet area of the air to the channel, m^2
c	thermal capacity of the internal plate, kJ/kg °C
C_d	discharge coefficient. Bansal [15]
C_p	specific air heat, kJ/kg °C
G	solar radiation, W/m^2
g	force of gravity = 9.81 m/s^2
H	height of the internal plate or glass plate, m
h_{c1}	heat transfer coefficient between internal plate and glass plate, W/m^2 K
h_{c2}	heat transfer coefficient between the external surface of the insulation and the room, W/m^2 K
h_{c3}	heat transfer coefficient between internal plate and the air to the exit of the channel, W/m^2 K
h_{r1}	radiation heat transfer coefficient between internal plate and glass plate, W/m^2 K
h_{r2}	radiation heat transfer coefficient between external surface of the insulation and the room, W/m^2 K
m	flow of air, kg/s
T_a	temperature of the air at the exit of the channel, K
T_e	environmental temperature, K
T_g	temperature on the glass plate surface, K
T_m	temperature on the internal plate surface, K
T_{room}	temperature of the room, K
T_w	temperature on the external surface of the insulation, K
t	time, s
U_1	global heat transfer coefficient between the glass and the environment, W/m^2 K
U_2	global heat transfer coefficient between the internal plate and the external surface of the insulation, W/m^2 K
V_m	volume of the internal plate, m^3
α_g	absorptance of the glass
β	volumetric expansion coefficient of air, K^{-1}
ρ_a	density of the air, kg/m^3
ρ	density of the internal plate, kg/m^3
$(\tau\alpha)$	transmittance absorptance product (glass plate and internal plate)

environment, also known as the thermal response of the system. Chen [5], Hung and Shiau [6] and Martin [7] varied the Rayleigh number between 0 and 10^{10}, analyzing how a heat collector behaves when the working substance varies. Morillón [8] studied the Fourier number importance between values of 5 and 44,000 in order to analyze how the wall responds with the capacity of heat storage as time passes. With regards to the formulation of the analytic models that describe the behavior of heat discharge systems, Duffin [9], Zalewski [10] and Fang [11] presented analytic models in transient state that allowed to know the behavior of some design variables in a Trombe wall. Hirunlabh [12] and Zalewski [13] present analytic models that give an account of the behavior of a Trombe wall in stationary state, reproducing the temperature history and natural convection characteristics on the massive wall. Guohui Gan [14] and Xiande Fang [11] used fluid dynamics software to simulate the thermal behavior of a Trombe wall.

However, the described analytic models do not contemplate neither the temperature of the air inside the construction to ventilate or the storage of heat in the internal plate or massive wall. It has probably been so because this effect is minimized or because it is believed that the air takes all the heat of the internal plate.

An experimental model was built that simulates the thermal behavior of this passive system when applied to walls. In the model, the advantage of solar energy is taken to warm up the air that circulates in the cavity formed by two vertical plates: a massive wall or storage plate (internal) and a glass plate (external).

The temperature of the internal plate with specific absorptance, thermal conductivity and heat storage properties is modified by solar radiation and becomes a heat accumulator. This heat is then transmitted to the air that is displaced along the cavity by natural convection. That air can be introduced into the room to warm it up, as is generally done with Trombe walls, or let it flow out to the exterior to induce air circulation inside the building.

2. Description of the analytic model

In order to state an analytic model to reproduce the most important features of a wall heat discharge system, the basic model proposed by Hirunlabh [12] was taken. The concept was modified to take into account the characteristics depicted in Fig. 1 under the following assumptions:

(a) The temperature of the interior of the room to be cooled is included in two heat transfer equations.
(b) The storage of heat in the internal plate is taken into account explicitly and
(c) The heat flux is taken to be unidirectional in the system.

The resulting equations are

Glass plate

$$GA\alpha_g - U_1A(T_g - T_e) + h_{r1}A(T_m - T_g) + h_{c1}A(T_a - T_g) = 0 \quad (1)$$

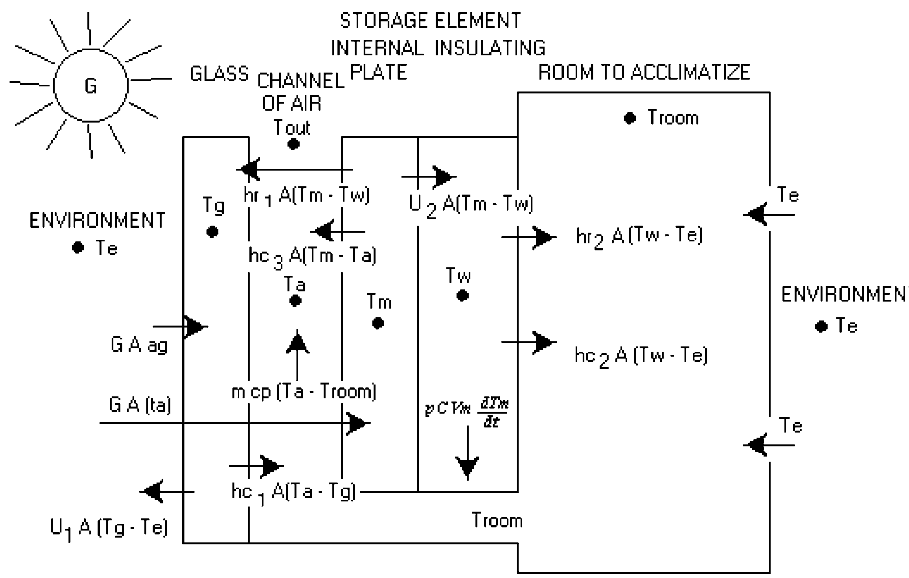

Fig. 1. Thermal behavior of the system of discharge of heat.

Air the interior of the cavity formed between the internal and glass plate

$$h_{c1}A(T_a - T_g) - h_{c3}A(T_m - T_a) + mC_p(T_a - T_{room}) = 0 \tag{2}$$

Internal plate

$$GA(\tau\alpha) - h_{c3}A(T_m - T_a) - h_{r1}A(T_m - T_g) - U_2A(T_m - T_w) = \rho c V_m \frac{dT_m}{dt} \tag{3}$$

Insulating protection of the internal plate

$$U_2A(T_m - T_w) - h_{r2}A(T_w - T_e) - h_{c2}A(T_w - T_e) = 0 \tag{4}$$

Flow of air generated in the cavity by natural convection. Bansal [15]

$$m = \rho_a C_d A_I [gH(T_a - T_{room})/T_{room}]^{1/2} \tag{5}$$

The solution of these equations turns out to be non-linear and in order to obtain a solution a numerical method must be used. In this case a computer code of common knowledge (Mathematica http://www.wolfram.com/products/mathematica/introduction.html) was used. The model involves the time variations of the environmental variables, the solar radiation and the environmental temperature. For the solar radiation the approximation is based on ASHRAE's [16], whereas the environmental temperature is calculated using a software elaborated by Tejeda [17], which allows to obtain the average hourly values of temperature and relative humidity per month for a specific region related to its geographical location. The maximum and minimum monthly average temperature values that are required by the software were taken from climatological data provided by the National Meteorological System.

3. Description of the experimental model

An experimental model was built based on a Trombe wall but utilized as a heat discharge system rather than a room warmer. The construction as well as the experimentation was developed in the Physics Laboratory of the Facultad de Estudios Superiores (School of Superior Studies) Cuautitlán of UNAM, under controlled ambient conditions. The experimental model simulates the phenomenon that is present in a heat discharge system, which can be employed either to ventilate the inside of a building or to prevent its overheating by solar radiation. It consists of two parallel plane plates (internal and external) separated by a space through which the air flows (channel). The inside plate consists of an aluminum plate 1/16 in. thick, so chosen because of its conductivity, thermal characteristics and low cost. This plate was used to simulate the massive wall or internal plate in the first seven tests. Material dependence was analyzed substituting this aluminum plate with a copper plate 1/16 in. thick in the last tests.

The second or external plate is a plane 4 mm glass plate. Dimensions are 1 m wide by 1.02 m length, and the separation between plates was kept at 5 cm, a dimension experimentally found appropriate to avoid turbulence at the cavity exit. In order to simulate the external environmental conditions (radiation and environmental temperature) resulting from latitude variation, orientation and climate type, among other factors, an arrangement of 20 electric resistors was selected, of the type employed in electric heaters, that provide a controllable heat flux from 0 to 1027 W (distributed evenly across the whole plate area of about 1 m^2). The heat flux is controlled by means of a variac. This heating device is protected with insulating material: 1/16 in. asbestos plate, 0.6 cm of asbestos–cement plate, 0.2 cm of glass fiber, 2 cm of polystyrene foam and 1.5 cm of wood, as shown in Fig. 1, with the purpose of diminish exterior losses and to assure the unidirectional flow that is procured with the model. The glass plate represents the external face of a system of heat discharge. The purpose of the electric heaters is to provide the heat flux equivalent to solar heat that the wall or internal plate would receive after being transmitted through the glass.

The instruments used in the experimentation were 11 digital multimeters, one ammeter, one powerstat variable transformer (variac), two circulation air thermometers, eight thermistor and two environment thermometers.

Since the objective it is to study the behavior of the discharge of heat in vertical walls, the experimental model was placed in vertical position and temperature measuring devices were distributed on the surface to get the following data:

Data	Notation	Quantity
Temperature of air at the inlet of the experimental model	T_e	1
Temperature of the air at the exit of the channel in the experimental model	T_a	1
Temperature on the surface of the internal plate	T_m	5
Temperature on the glass plate surface	T_g	2
Temperature on the surface of the insulating material protecting		
The internal plate	T_w	1

The sensors were distributed along the internal plate with the purpose to register the temperature at the surface. The distribution was: five thermistor in the surface of the internal plate (T_m), two thermistor on the glass plate surface (T_g) and one upon the surface of the insulating material covering the internal plate (T_w) to determine the heat loss through the insulating material to the room. The temperature probes were placed at the air inlet and outlet in the experimental model to get the temperature variation in the channel formed by both parallel plates. To simulate the heat flux by means of resistors, a multimeter and ammeter were placed between the experimental model and a variac. The variac was used because it allowed modifying the voltage provided from 0% to 100% its nominal value and worked as a regulator in the event of a current increase caused by the rupture of some of the resistors being used.

3.1. Experimental development

The heat flux supply was provided in two ways and in both cases the reading was made manually. When the heat flux was provided by the resistors, a voltage was applied to the resistors until a uniform heat flow between them was obtained, that is, until stabilization. Immediately afterwards, starting with an initial value of 150 W/m^2, the power was increased in steps of 250, 350, 450 and 600 W/m^2. Four tests (with aluminum plate) were carried out in the model and it was observed that during the experiments, the ambient temperature varied due to atmospheric conditions. These variations were recorded to be taken into account when applying the analytic model in order to obtain realistic results of the heat discharge systems. On the other hand, in the cases when the heat flux was provided by solar radiation, the model was oriented to the south in a way that it received the solar radiation during most of the day. A pyranometer was oriented in a vertical mode, parallel to the experimental apparatus. Readings from the temperature sensors were taken every 30 min between 9 and 17 h. Aluminum and copper plates were used in each test.

4. Results and discussion

In Fig. 2 the behavior of the temperature in the surface of the internal plate and the temperature of the air at the exit of the cavity of the four carried out tests, is presented, using the arrangement of resistances to generate the flow of heat in the time. A similar behavior is observed in the tests with small variations. In Fig. 2a it is observed that the temperature in the surface of the internal plate (aluminum) did

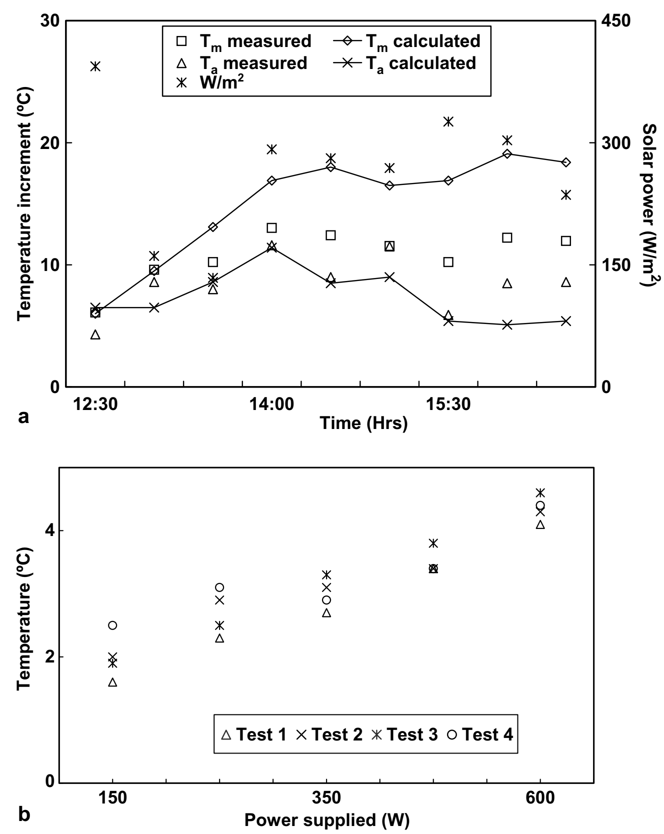

Fig. 2. Behavior of the experimental model when increasing the flow of heat with time using resistances. Values obtained above the environmental temperature. (a) Temperature in the surface of the internal plate. (b) Temperature of the air to the exit of the experimental model.

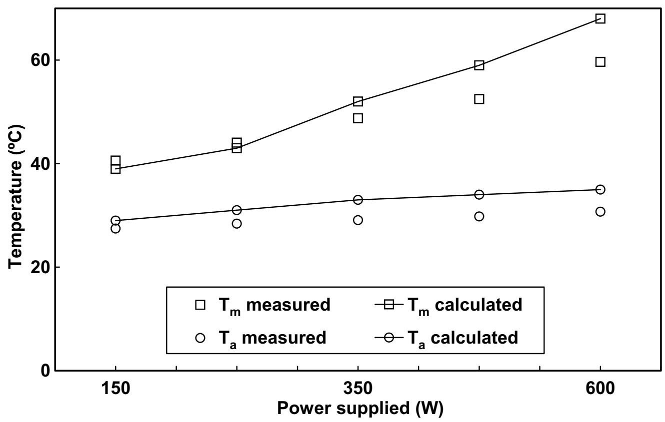

Fig. 3. Comparison of the measured and calculated results for the temperature of the internal plate surface (T_m) and the temperature of the air at the exit of the cavity (T_a).

not have a variation larger than 2 °C among the tests, while in Fig. 2b it can be observed that it did not have a difference larger than 1 °C for the temperature of the air at the exit of the cavity.

In Fig. 3 the comparison of the results measured with those calculated is presented, the difference observed is not bigger to 5 °C for the temperature of the internal plate (aluminum) and 4 °C for the temperature of the air to the exit of the cavity.

In Fig. 4 the behavior of the temperature in the surface of the internal plate (aluminum) exposed to the solar radiation is presented. It is observed that the heating is not uniform along the aluminum plate detecting a variation of temperature along its surface of around 8 °C.

In Fig. 5 the comparison of the results calculated with those measured using to the solar radiation as supply of the heat flow is presented, a difference not larger than 5 °C is observed, for the temperature of the surface of the internal plate (aluminum) and of 5.5 °C for the temperature at the exit of the cavity.

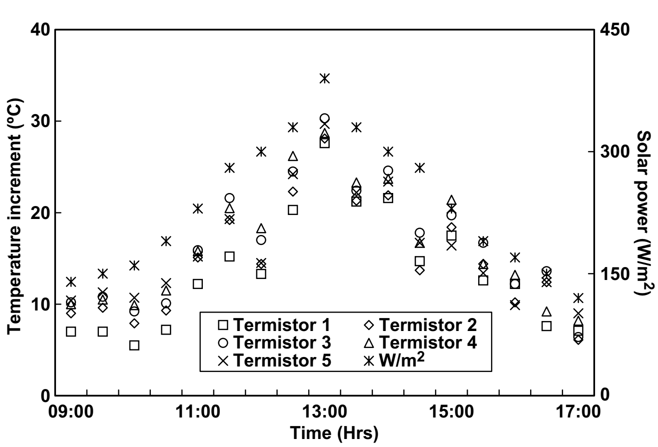

Fig. 4. Internal plate surface temperature (T_m) above environment with time, aluminum plate was used.

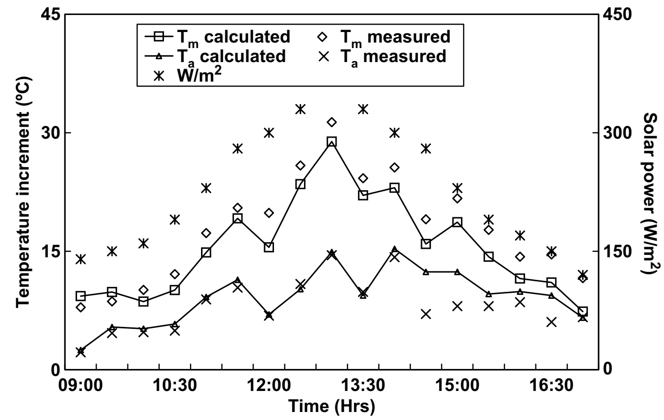

Fig. 5. Comparison of the measured and calculated results for the temperature of the internal plate surface (T_m) and the temperature of the air at the exit of the cavity (T_a). Aluminum plate. Values obtained above the environmental temperature.

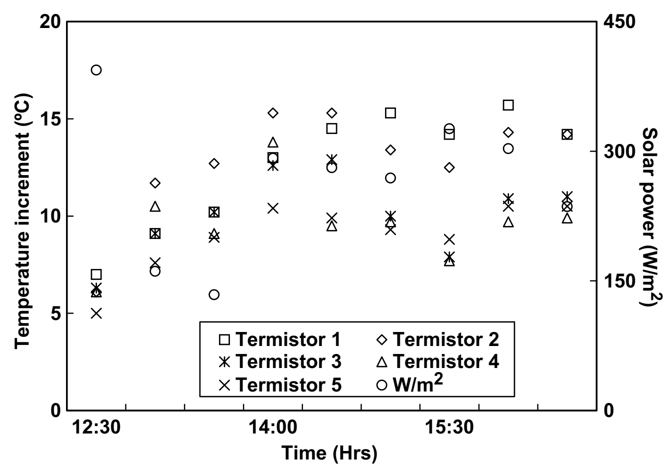

Fig. 6. Internal plate surface (T_m) against the heat flux variation against time. Copper plate. Values obtained above the environmental temperature.

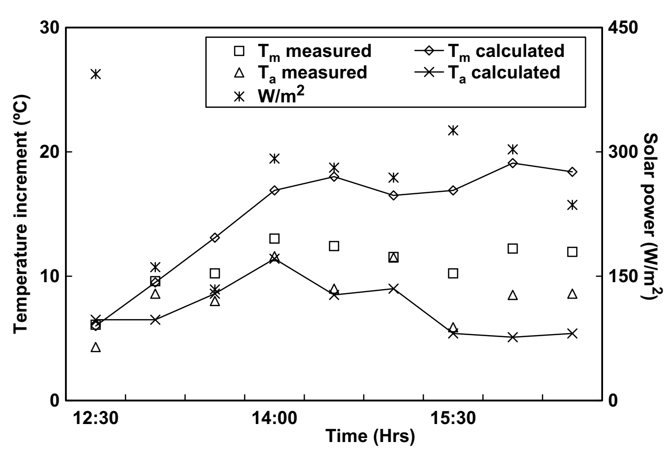

Fig. 7. Comparison of the measured and calculated results for temperature of the internal plate surface (T_m) and the temperature of the air at the exit of the cavity (T_a). Copper plate. Values obtained above the environmental temperature.

In Fig. 6 the behavior of the temperature in the surface of the internal plate (aluminum) exposed to the solar radiation is presented. It was observed, contrary to the aluminum plate, that the heating is uniform among the temperatures in the selected points in the surface, due to the thermal conductivity, presenting a variation of 7 °C.

In Fig. 7 the comparison among the calculated results and those measured using copper plate and solar radiation as the source of the heat flow of heat is presented. It is observed that a variation of 12 °C exists for the temperature in the surface of the copper plate and of 6 °C for the temperature of the air to the exit of the cavity.

5. Conclusions

The general trend of heat fluxes and temperatures at the experimental set up is appropriately described by the analytic model. With regards to data obtained from the solar experimental test and from the analytic model, the variation is not higher than 5 °C for the internal plate and 4 °C for the air temperature at the outlet of the cavity. In the case where the heat flux is provided by solar radiation, the differences between the obtained data in the experimental test and with the analytic model, the variation is not higher than 5 °C for the internal plate and 5.5 °C for the air temperature at the outlet of the cavity.

The analytic model proposed may be employed to know in advance the behavior of a heat discharge wall system just by defining the dimensions of the heat discharge system and the environmental conditions at the place where it is intended to be used. The comparisons between results calculated and those obtained from experiments lead to believe that the lumped parameter model can reproduce, with appropriate certainty, temperature variations with heat flows. However, it is necessary that tests be carried out in large scale prototypes to evaluate if length or height dimensions are additional variables that must be attended separately or if the lumped parameter approach can still be trusted.

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