OPTIMIZATION AND COMPARATIVE THERMAL EVALUATION OF FOUR DIFFERENT SOLARIUM-CUM-SOLAR HOUSES

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(Received 11 June 1993; received for publication 18 April 1994)

Abstract—In this communication, four designs of sunspaces are conceived for a one room residential apartment. Analytical expressions have been derived using energy balances of the different components of the structure and a comparative analysis in terms of sunspace and living room temperatures have been presented. For the same glass area exposed to sun-rays, a comparative numerical evaluation of the four solarium-cum-solar houses is also presented. It is concluded that (a) the south inclined glass solarium at the optimum angle gives better thermal comfort as compared to others for the same area of glass exposed to solar radiation and (b) the living room temperature fluctuation increases with an increase in glass area and better load levelling is achieved by incorporating a larger thermal mass inside the living room.

Sun space Passive heating Thermal load

NOMENCLATURE

\[ A_w = \text{Area of isothermal mass (m}^2\text{)} \]
\[ A_s = \text{Area of sunspace floor (m}^2\text{)} \]
\[ A_l = \text{Area of living room floor (m}^2\text{)} \]
\[ A_d = \text{Area of different walls and roof of sunspace (m}^2\text{)} \]
\[ A_{dl} = \text{Area of different walls and roof of living room (m}^2\text{)} \]
\[ A_{lkr} = \text{Area of link wall (m}^2\text{)} \]
\[ A_{ls} = \text{Area of south glass cover of sunspace (m}^2\text{)} \]
\[ C_s = \text{Specific heat of air (J/kg°C)} \]
\[ C_{is} = \text{Specific heat of isothermal mass (J/kg°C)} \]
\[ C_w = \text{Specific heat of water (J/kg°C)} \]
\[ h_{s} = \text{Heat transfer coefficient from isothermal mass to room (W/m}^2\text{°C)} \]
\[ h_{f} = \text{Heat transfer coefficient from floor to ground (W/m}^2\text{°C)} \]
\[ h_{h} = \text{Heat transfer coefficient from floor to sunspace (W/m}^2\text{°C)} \]
\[ h_{a} = \text{Heat transfer coefficient from floor to living room air (W/m}^2\text{°C)} \]
\[ h_{c} = \text{Heat transfer coefficient from one water column to other through trap material (W/m}^2\text{°C)} \]
\[ h_{i} = \text{Heat transfer coefficient from one water column to sunspace air (W/m}^2\text{°C)} \]
\[ h_{k} = \text{Heat transfer coefficient from second water column to living room air (W/m}^2\text{°C)} \]
\[ I_{s} = \text{Solar radiation incident on south glass cover (W/m}^2\text{)} \]
\[ M_{aw} = \text{Mass of air in sunspace (kg)} \]
\[ M_{al} = \text{Mass of air in living room (kg)} \]
\[ M_{iw} = \text{Mass of isothermal mass in living room (kg)} \]
\[ M_{iw} = \text{Mass of water in one column of transwall (kg)} \]
\[ M_{is} = \text{Mass of water in second column of transwall (kg)} \]
\[ T_{a} = \text{Ambient temperature (°C)} \]
\[ T_{s} = \text{Temperature of floor of sunspace (°C)} \]
\[ T_{l} = \text{Temperature of floor of living room (°C)} \]
\[ T_{is} = \text{Temperature of isothermal mass (°C)} \]
\[ T_{as} = \text{Temperature of sunspace air (°C)} \]
\[ T_{al} = \text{Temperature of living room air (°C)} \]
\[ T_{iw} = \text{Temperature of one water column (°C)} \]
\[ T_{is} = \text{Temperature of second water column (°C)} \]
\[ T_{g} = \text{Temperature of ground (°C)} \]
\[ U = \text{Overall heat transfer coefficient from zone 1 to ambient air through glass/wooden (W/m}^2\text{°C)} \]
\[ U = \text{Overall heat transfer coefficient from zone 2 to ambient air through wooden material (W/m}^2\text{°C)} \]

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835
Greek letters
\[ \tau = \text{Transmittivity of glass cover} \]
\[ \delta L_1 = \text{Thickness of water column (m) (1 and 2 refers to first and second water column of transwall)} \]
\[ \delta L_2 = \text{Thickness of trap material (m)} \]
\[ \epsilon = \text{Emissive power} \]
\[ \eta = \text{Extinction coefficient of water (m}^{-1}\text{)} \]
\[ \mu = \text{Extinction coefficient of trap material (m}^{-1}\text{)} \]
\[ \delta = \text{Fraction of solar radiation with extinction coefficient, } \eta \]

Subscripts
1, 2 = Zone 1 and 2, respectively
E, W, N, S = East, west, north and south
f = Floor
g = Glass

INTRODUCTION

Passive solar design seeks to maximize, within other imposed constraints, the useful contribution that the sun can make to the energy demands of buildings. It does this by manipulating the architectural elements to provide the best environmental comfort and energy economy. The main targets are arrangements and orientation of rooms and areas within a building. In winter, various passive methods can be integrated for thermal comfort with a minimum swing in living room temperature [1]. In passive methods, direct and indirect gain are two ambiits of heating the house. The direct gain method employs trapping of solar radiation and can be achieved by the greenhouse effect, i.e. using sunspace with a glass wall in the south. It is very popular and one of the most common design characteristics of winter houses. In the indirect gain method, solar radiation is absorbed in a storage mass during the high temperature hours, and heat is released to the living room during the low temperature hours (night). The swing in room temperature and thermal comfort depends upon different types of storage mass—(i) transwall [2, 3], (ii) Trombe wall [4] and (iii) water wall [5].

Monitored results for sunspaces are scarcely available, and whatever does exist is related to heating load [6]. The thermal performance of sunspaces attached to already existing buildings in cold climatic conditions is examined experimentally by Schoenam et al. [7]. Thermal evaluation of a proposed prototype winter house is done by Jha et al. [8] incorporating water as the isothermal mass, while an analytical model of a solarium has been presented by Yadav and Tiwari [9]. The design of a non-airconditioned passive solar house for the cold climate of Srinagar (India) is presented by Tiwari [10]. He has incorporated the concept of the water drum and transwall for indirect heating in his design. In all these analyses of indirect gain, the water wall and/or transwall is used as the south wall of the solarium.

In the present design concepts conceived, both direct as well as indirect heating concepts are used to trap solar energy. A water wall/transwall is used for partition, and a glass wall is used as the south wall of the solarium. This concept has an advantage of minimizing radiation loss from the water wall/transwall during low sunshine hours. In low sunshine hours, radiation loss is more than the incident sun radiation. Therefore, during these periods, the south wall is usually insulated in all earlier proposed models. This problem is avoided in the present design concept to a large extent. Use of a south glass allows for a longer sunshine period, since it traps the radiation from the water wall/transwall. An attempt in this direction is earlier made by Tiwari and Kumar [11]. In this communication, four different conceived designs of sunspace are attached to a one room residential apartment. Their comparative study in terms of living room temperature and sunspace temperature has been carried out. Analytical expressions are derived using energy balances of the different components. The transwall has been taken as the link wall of the living room and sunspace. On the basis of thermal evaluation, it is concluded that

(i) the south inclined glass solarium gives better thermal comfort as compared to other solariums if the area of the glass exposed to solar radiation is the same, and
(ii) the living room temperature fluctuates with an increase in glass area and load levelling can be achieved by incorporating a larger thermal mass inside the living room.
DESIGN OF PROPOSED SOLAR HOUSE

The floor plan of the proposed solar house has been shown in Fig. 1. The living room (zone 2) is connected with the sunspace (zone 1) by a link wall, i.e., transwall (Fig. 1). The other walls and roof of the living room are made of wooden material to minimize heat losses during the off-sunshine hours. There is a provision of a door in the east wall of the living room (zone 2 of Fig. 1). Cross-sectional views of four different designs of sunspaces attached to the living room are also shown in Fig. 2. All the sunspaces are constructed of glass walls and wooden roof as well as wooden floor. The roof of the first sunspace (SS1) is inclined to the south at a particular angle to receive maximum solar radiation. The second sunspace (SS2) is similar to SS1 except that it is constructed with a horizontal roof. This type of sunspace is generally used in the cold climates. The third design of sunspace (SS3) has inclined glass in the south wall. The inclination of the glass is kept at the optimum angle of 30° to receive maximum solar radiation in Srinagar. SS4 is the fourth type of design of solarium. It also has optimally inclined glass in the south wall. In this design, some portion of the glass wall is vertical. It is important to note that the exposed glass area of each of the designs has been kept the same. The different design parameters of the living room and the sunspaces are given in Table 1.

THERMAL ANALYSIS

The following assumptions have been made before writing the energy balances for the sunspace and living room, respectively,

(i) there is no temperature gradient in zones 1 and 2,
(ii) all glass walls are insulated during off-sunshine hours to avoid heat loss,
(iii) there is no stratification in the water column of the transwall,
(iv) heat gain through the semi-transparent surfaces by conduction is negligible due to small thicknesses and
(v) the heat capacity of air in zones 1 and 2 is negligible as compared to the water mass of the link wall.

(a) Link wall (transwall)

\[
A_{w1} T_z(t) \left[ 1 - \sum \delta_j \exp(-\eta_j \delta L_{w1}) \right] = M_{w1} C_w \frac{dT_{w1}}{dt} + h_1(T_{w1} - T_{R1}) A_L + h_2(T_{w1} - T_{w2}) A_L
\]  

\[
A_{w2} \sum \delta_j \exp(-\eta_j \delta L_{w1}) \sum \exp(-\mu_j \delta L_T) \left[ 1 - \sum \delta_j \exp(-\eta_j \delta L_{w2}) \right] 
= M_{w2} C_w \frac{dT_{w2}}{dt} + h_2 A_L(T_{w2} - T_{R2}) - h_1(T_{w1} - T_{w2}) A_L.
\]  

![Fig. 1. Floor plan of proposed solar house.](image-url)
Rearranging the above equations,

\[
M_u C_u \frac{dT_{w1}}{dt} + (h_1 + h_s) A_L T_{w1} - h_1 A_L T_{R1} - h_s A_L T_{w2} = A_w \tau L_s(t) \left[ 1 - \sum \delta_i \exp(-\eta_i \delta L_{w1}) \right] \tag{3}
\]

\[
M_w C_w \frac{dT_{w2}}{dt} + (h_2 + h_s) A_L T_{w2} - h_2 A_L T_{R2} - h_s A_L T_{w1} = A_w \tau L_s(t) \left[ 1 - \sum \delta_i \exp(-\eta_i \delta L_{w2}) \right] \tag{4}
\]
Table 1. Design parameters of solar house

<table>
<thead>
<tr>
<th>Components of zone 1</th>
<th>Components of zone 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Floor (wood)</td>
<td>6 × 3.5</td>
</tr>
<tr>
<td>North wall</td>
<td></td>
</tr>
<tr>
<td>South (glass)</td>
<td></td>
</tr>
<tr>
<td>vertical</td>
<td>6 × 4</td>
</tr>
<tr>
<td>inclined</td>
<td></td>
</tr>
<tr>
<td>both</td>
<td></td>
</tr>
<tr>
<td>South (wood)</td>
<td>6 × 3</td>
</tr>
<tr>
<td>Link wall</td>
<td></td>
</tr>
<tr>
<td>East (glass)</td>
<td>3 × 4</td>
</tr>
<tr>
<td>East (wood)</td>
<td>12</td>
</tr>
<tr>
<td>West (glass)</td>
<td>3 × 4</td>
</tr>
<tr>
<td>West (wood)</td>
<td>12</td>
</tr>
<tr>
<td>Roof</td>
<td>24</td>
</tr>
<tr>
<td>Roof (inclined)</td>
<td></td>
</tr>
</tbody>
</table>

(b) Sunspace

\[ A_{in}h_{in}(T_{in} - T_{R1}) + h_{in}(T_{wi} - T_{R1})A_L = M_{in}C_{in}\frac{dT_{R1}}{dt} + \sum_{i}^{4} U_{i}A_{i}(T_{R1} - T_{i}). \] (5)

Floor of Sunspace

\[ h_{in}A_{in}(T_{in} - T_{R1}) = h_{in}A_{in}(T_{in} - T_{in}) \Rightarrow T_{in} = [h_{in}T_{R1} - h_{in}T_{in}]/(h_{in} - h_{in}). \] (6)

Now, the first order differential equation for \( T_{R1} \) can easily be written using expression of \( T_{in} \) as,

\[ M_{in}C_{in}\frac{dT_{R1}}{dt} + \left[ \sum_{i}^{4} U_{i}A_{i} + h_{in}A_{n} - h_{in}h_{in}/(h_{in} - h_{in}) \right]T_{R1} \]

\[ = \sum_{i}^{4} U_{i}A_{i}T_{i} + h_{in}A_{n}T_{in} - [h_{in}A_{n}/(h_{in} - h_{in})]T_{in}. \] (7)

where \( U_{i} \) is different for day and night due to movable insulation over the glass cover and \( i = S, E, W \) and roof of the sunspace (total area including glass of sunspace).

(c) Living room

\[ I_{t}(t) \sum_{j} \delta_{j} \exp(-\eta_{j}\delta L_{w1} + \delta L_{w2})/\mu \exp(-\mu_{j}\delta L_{i}) = M_{is}C_{is}\frac{dT_{R2}}{dt} + h_{is}A_{is}(T_{R2} - T_{i}) \]

\[ + \sum_{j}^{4} U_{j}A_{j}(T_{R2} - T_{j}) + h_{is}A_{is}(T_{R2} - T_{2}). \] (8)

Floor of Living Space

\[ h_{is}A_{is}(T_{is} - T_{R2}) = h_{is}A_{is}(T_{is} - T_{in}) \Rightarrow T_{in} = [h_{is}T_{R2} - h_{is}T_{in}]/(h_{is} - h_{is}). \] (9)

Using equations (8) and (9), one may get,

\[ M_{is}C_{is}\frac{dT_{R2}}{dt} + \left[ \sum_{j} U_{j}A_{j} + h_{is}A_{is} + h_{is}A_{is}/(h_{is} - h_{is}) \right]T_{R2} = \sum_{j} U_{j}A_{j}T_{j} + h_{is}A_{is}T_{i} \]

\[ - h_{is}A_{is}/(h_{is} - h_{is})T + A_{is}I_{t}(t) \sum_{j} \delta_{j} \exp(-\eta_{j}\delta L_{w1} - \mu_{j}\delta L_{i})\left[ 1 - \sum_{j} \delta_{j} \exp(-\eta_{j}\delta L_{w2}) \right]. \] (10)

where \( j = E, W, N \) and roof of the living room.

(d) Isothermal mass

\[ h_{is}A_{is}(T_{R2} - T_{i}) = M_{is}C_{is}\frac{dT_{i}}{dt}. \] (11)
Room air temperature $T_{R_1}$ and $T_{R_2}$ can be obtained by solving the above differential equations of first order.

**Index of Thermal Comfort (IOC)**

The index of thermal comfort (IOC) or thermal load levelling is used to measure thermal comfort in a house. It is expressed in terms of the difference in maximum and minimum living room temperatures. Therefore, the IOC is desired to be a minimum. Thermal comfort increases with a decrease in the IOC. Mathematically, it may be expressed as,

$$IOC = \frac{T_{R_{max}} - T_{R_{min}}}{T_{R_{max}} + T_{R_{min}}}$$  \hspace{1cm}(12)

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Fig. 3. Solar radiation on different walls.
NUMERICAL COMPUTATIONS AND RESULTS

In order to compute the temperatures of the two rooms and water columns numerically, the following dimensions are considered:

\[ \delta L_1 = 0.01 \text{ m}, \quad \delta L_{a1} = \delta L_{a2} = 0.05 \text{ m}, \quad \rho_w = 1000 \text{ kg/m}^3, \quad \rho_a = 1.2 \text{ kg/m}^3 \]

\[ C_w = C_{si} = 4190 \text{ J/kg}, \quad M_w = 100 \text{ kg}, \quad h_{si} = 10 \text{ W/m}^2 \circ C \]

\[ U_i = 8 \text{ W/m}^2 \circ C \text{ (during day)} = 2 \text{ W/m}^2 \circ C \text{ (during night)} \]

\[ U_j = 0.4 \text{ W/m}^2 \circ C, \quad h_t = 20 \text{ W/m}^2 \circ C = h_s. \]

The different design parameters of the living room and the sunspaces are given in Table 1. Climatic data, i.e. solar radiation and ambient temperature, considered for the analysis are of Srinagar, Jammu and Kashmir (India). Solar radiation incident on the different walls—east, west, south, north and south inclined walls has been calculated by Liu and Jordan, Duffie and Beckman [12] and is shown in Fig. 3. The total radiation on the inclined surface at 50° comes out to be a maximum because of the optimum tilt angle (\( \phi + 15^\circ \), following Duffie and Beckman [12], where \( \phi \) is the latitude of Srinagar = 34°).

Four different designs of sunspaces have been considered for computation. In this analysis, the exposed area of glass in the south wall and the dimension of the living room is kept the same. There are only minor differences between sunspaces which may be considered negligible from the comparison point of view. Living room temperatures have been calculated for each of the sunspaces, and indices of thermal comfort have been determined. Table 2 shows the maximum and minimum temperature up to steady state condition for the 1st, 2nd and 3rd consecutive days. The index of thermal comfort for each of the sunspaces is also shown. As the structure attains a steady state condition, the IOC decreases to its minimum. In the steady state condition, SS3 gives the maximum thermal comfort, i.e. its IOC is a minimum. The variation in thermal load levelling has also been studied for different isothermal masses kept in the living room for the best design of sunspace (Fig. 4). On the basis of the numerical computations, it is concluded that:

![Fig. 4. Variation in IOC for different isothermal mass.](image-url)
(a) the design of sunspace which has the inclined glass wall gives the maximum living room temperature and minimum thermal load levelling because the solar intensity is a maximum for the optimum tilted glass cover, and
(b) the thermal load levelling or index of thermal comfort of the living room varies with the different designs of sunspaces.

Acknowledgement—The authors express their thanks to Professor N. C. Bhagat, Head, Department of Physics, University of Bihar for valuable discussion and encouragement.

REFERENCES