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Thermal Characteristics of High Thermal Mass Passive Solar Buildings

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Abstract:

Thermal behaviour of a high thermal mass residential building with a conservatory located in Hockerton, U.K was studied using SUNREL and EnergyPlus building energy simulation software. The building was designed to operate with no conventional space heating during the winter. Measured air temperatures of the inside rooms of the building show a steady value throughout the year with minimal diurnal temperature swings. Simulation results from both software indicate that the accuracy of the predicted zone air temperatures depends on inter zone solar transfer through transparent surfaces. SUNREL does not explicitly calculate solar transfer between zones. As such, predicted air temperatures of the zones that do not possess external fenestration largely depend on user-defined solar transfer fractions. Although EnergyPlus has a detailed distribution model, it treats the inter-zone solar transfer as diffuse radiation. This tends to underestimate the internal air temperatures in colder months and overestimates the same in the warmer months. Depending on the massiveness of the building, annual simulations have to be carried out for a period longer than a year using the same weather data to account for the thermal energy accumulation in the initial period of the simulation

Key Words: Passive Solar Houses; Thermal Mass; Thermal Characteristics, Simulation

1. Introduction

In the past few decades use of thermal mass in passive solar houses has attracted much attention due to the high cost of winter heating. The goal is to achieve ‘zero-heating’ while maintaining the required thermal comfort levels inside the building in heating-dominated climates. Thus, utilisation of solar energy for space heating plays an important role towards achieving this goal. Solar energy can be made available immediately in a building or it can be stored in the thermal mass associated with the building. If the solar radiation transmitted through the fenestration is allowed to transfer into the interior environment by natural convection, the building is said to be a ‘passive solar building’.

Due to varying amounts of solar radiation received by the interior zones, zone air temperatures of a passive solar building may fluctuate with high amplitudes on a diurnal basis. This undesirable situation makes the occupants thermally uncomfortable. If on the other hand the excess amount of solar radiation received is stored in the thermal mass and utilised later at night, the degree of diurnal temperature swing can be reduced. The general notion is that the overall thermal resistance of the building envelope determines the mean inside air temperature while the temperature swing (difference between maximum and minimum temperatures) is dictated by the thermal mass of the building.

Lund[1] demonstrated using a lumped-parameter model that the temperature swing in a simple passive solar building is a strong function of the amount of thermal mass used and the former is inversely proportional to the latter. Although it appears that the increase in the amount of thermal mass would phase out the temperature swing completely, the embodied energy in the mass may lead to a non-sustainable design. Further, a recent study by Mithraratne and Vale [2] showed that the fractions of transmitted solar received by the mass and inside air are also contributing factors in determining diurnal temperature fluctuations. The results of the experimental study conducted by Bellamy and Mackenzie[3] on two buildings with different construction types revealed that the massive building provided superior thermal comfort over the building with light construction in the summer. They also reported that the overall winter heating cost in the thermally massive building was higher than that of the light construction building. A similar conclusion was drawn from the results obtained by simulating passive solar houses by Willoughby[4] and Barnard et. al [5]. Simulation results from both studies indicated that the incorporation of thermal mass incurs additional heating in the winter. This can be attributed to the intermittent heating schedules in the winter as the mass loses its stored energy both to the inside and to the outside during off-heating period. When the building is re-heated, it is not only necessary to raise the temperature of the air but the mass temperature as well. The additional energy for the intermittent heating with the mass can however be minimised by incorporating a high level of thermal insulation to reduce heat losses from the mass. Further, the use of mass and insulation at Hockerton showed that extra intermittent heating can be eliminated.

It is thus clear that the thermal mass is an integral part of passive solar buildings. The understanding of the interaction between the thermal mass and the passive solar house is an important step involved in the process of designing such buildings. Use of thermal simulation software is a very effective option towards this goal. This study looks at some of the key parameters that are required to be considered when simulating thermally massive passive solar houses. Two building energy simulation programmes; SUNREL[6] and EnergyPlus[7] have been used to simulate a high thermal mass passive solar house located in Hockerton, UK[8].

2. SUNREL and EnergyPlus models

SUNREL[6] is a building energy simulation software developed by the National Renewable Energy Laboratory (NREL), USA. EnergyPlus[7] was jointly developed by the University of Illinois at Urbana Champaign (UIUC) and the Berkeley National Laboratory, USA. It is also used for building energy analyses and has a number of additional functionalities compared to SUNREL. Both packages have been developed with a variety of applications in mind. In this section information and modelling approaches only relevant to the present study are discussed. For further details in numerical algorithms and solution procedures the reader is referred to references [6] and [7].

Distribution of transmitted solar radiation:

SUNREL reads in hourly beam and total global horizontal radiation values from the weather data file. With these two inputs and the sun’s altitude, the direct and the diffuse components are then computed. SUNREL uses an isotropic sky radiation model in which the intensity of sky radiation is considered to be the same for any surface orientation. The view factors are taken as geometric view factors.

EnergyPlus, on the other hand, implements the anisotropic model of Perez et. al[9] to determine the sky radiation. The sky view factor in EnergyPlus radiation model depends on a number of parameters including the surface orientation. The ground view factor is a user-defined parameter and the user is expected to consider other factors such as obstructions around the surface when defining it.

Inter zone solar transfer and surface solar distribution:

Generally passive solar buildings consist of different zones. For instance, a typical passive solar house may contain a conservatory to trap the transmitted solar energy through the exterior fenestration and adjacent interior rooms. These interior rooms, which do not have external fenestration, could receive solar radiation in two ways. Firstly they may receive direct beam solar transmitted through the external fenestration and then through transparent surfaces (windows and glass doors) in the internal partition walls. They may also receive multi-reflected beam and diffuse radiation from the adjacent zones. Fig. 1 depicts these two possibilities of short wave radiation transfer between zones.

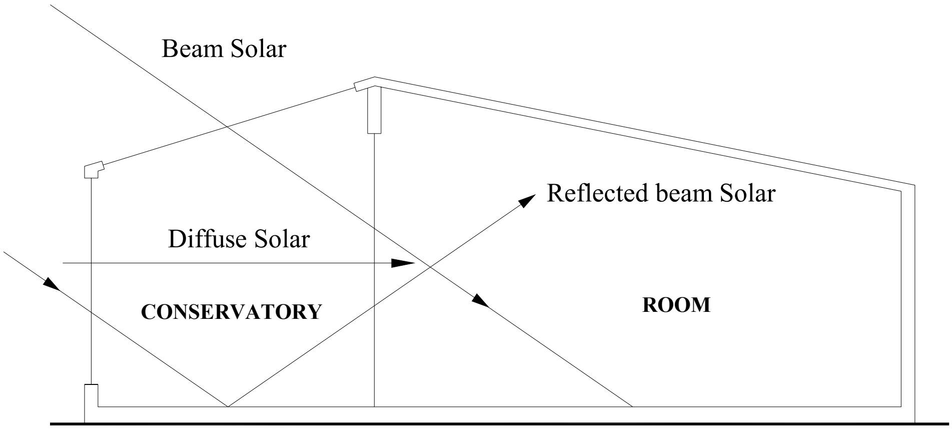

Fig. 1. Solar transfer to interior zones

SUNREL relies on the user input values for the fraction of solar radiation transferred to other zones. It can be input as a schedule, as the angle of incidence of the direct beam radiation changes with time. Once the total solar radiation in a thermal zone is determined, the next important step is to assign the fractions absorbed by walls, by the zone air, and the fraction lost. These distribution factors are again user dependent inputs. An alternative way of assigning the fractions absorbed by each wall in the zone is to use the key word ‘area’. This option will distribute the net solar radiation available in a zone, after inter-zone transfers, losses to outside, and the amount absorbed by the air, uniformly based on the wall area.

EnergyPlus, on the other hand, has a detailed distribution model with a minimum number of user dependent inputs. The user can however choose one of the three distribution options available. Of the three options, minimal-shadowing, full-exterior and full-interior-exterior, the details of the last distribution scheme are discussed here. In this model, the beam solar radiation falling onto each surface is computed by projecting the sun’s rays. The amount of beam radiation absorbed by each surface is determined by surface solar absorptance and the sunlit area on the surface. Any reflected beam is then added to the transmitted diffuse (both sky and ground-reflected) component and the resultant amount is uniformly distributed over all surfaces including transparent surfaces according to the area and solar absorptance. Thus the re-transmitted component through exterior fenestration contributes to the main solar loss from a zone. For interior zones with transparent surfaces in partition walls, both the beam and diffuse solar incident are treated as diffuse radiation, which means both components incident on the transparent surfaces are multiplied by a fixed diffuse transmittance value.

3. The high thermal mass house

A high thermal mass, passive solar residential building located in Hockerton, UK is chosen for the simulations. It is one of the five terrace houses in the Hockerton Housing Project[8], the UK's first earth-covered, self-sufficient housing development. These buildings were designed to operate with no conventional space heating during the winter. The orientation of the building allows maximum winter solar gain. A south-facing conservatory runs the full width of the dwellings and all internal rooms are south facing.

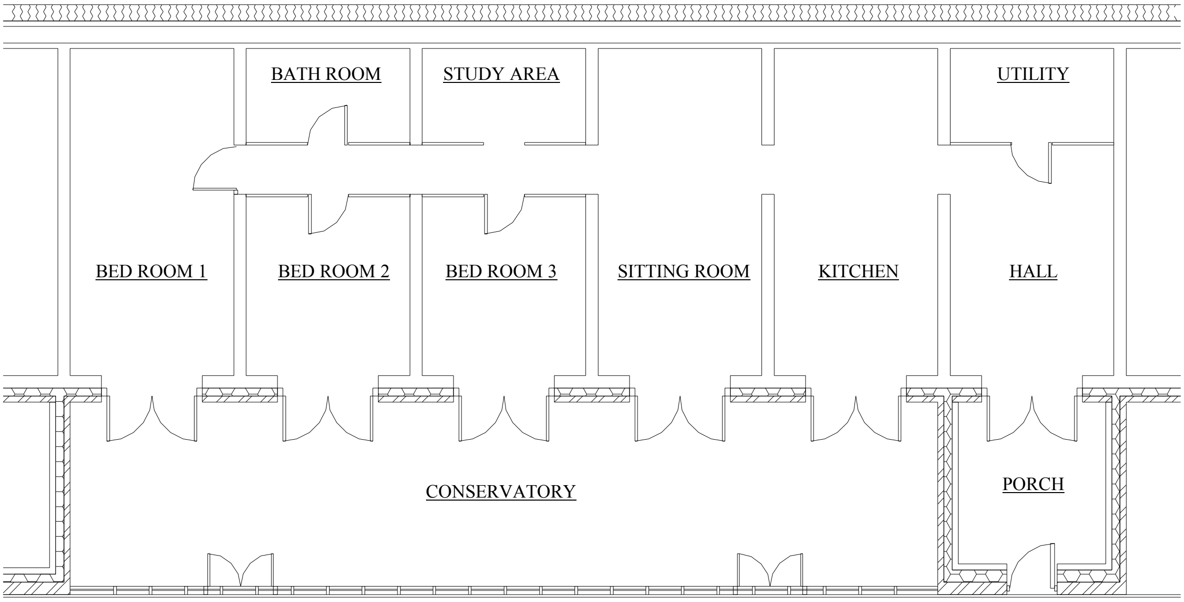

Fig. 2. Floor plan of high thermal mass passive solar house

The building fabric is principally concrete; the roof and slabs are of 300 mm reinforced concrete and north facing back wall is of 450 mm concrete. The internal walls are at 3.2 m intervals and are constructed of 200 mm concrete blocks. The entire structure has an external surround of 300 mm expanded polystyrene, providing very high thermal insulation. The roof, walls and floor have a U-value of 0.11 $W/m^2.K$. The windows in the partition wall that open onto the conservatory are triple-glazed with low-emissivity(low-e) coatings. The fenestration on the roof and the south-facing wall of the conservatory consists of double-glazing. The solar space heating system is completely passive and heat transfer from the conservatory to the interior rooms can be facilitated by opening the windows if required. The floor plan and a typical section with construction details of one of the houses are depicted in figs. 2 and 3. As can be seen from fig. 1, the interior rooms can receive direct beam as well as diffuse solar through the windows in the partition wall between the conservatory and the rooms.

Simulation model:

In order to study the thermal characteristics, the building must be represented by one or more thermal zones. Many building energy simulation software packages use the thermal zone concept to define thermal properties necessary for the simulation. The high thermal mass house used for the present study is zoned as shown in fig. 4. Since the exterior surfaces of the east and west walls are the interior surfaces to the room zones in the adjacent houses, it is assumed that there is no heat transfer between the exterior surface of these walls and the air.

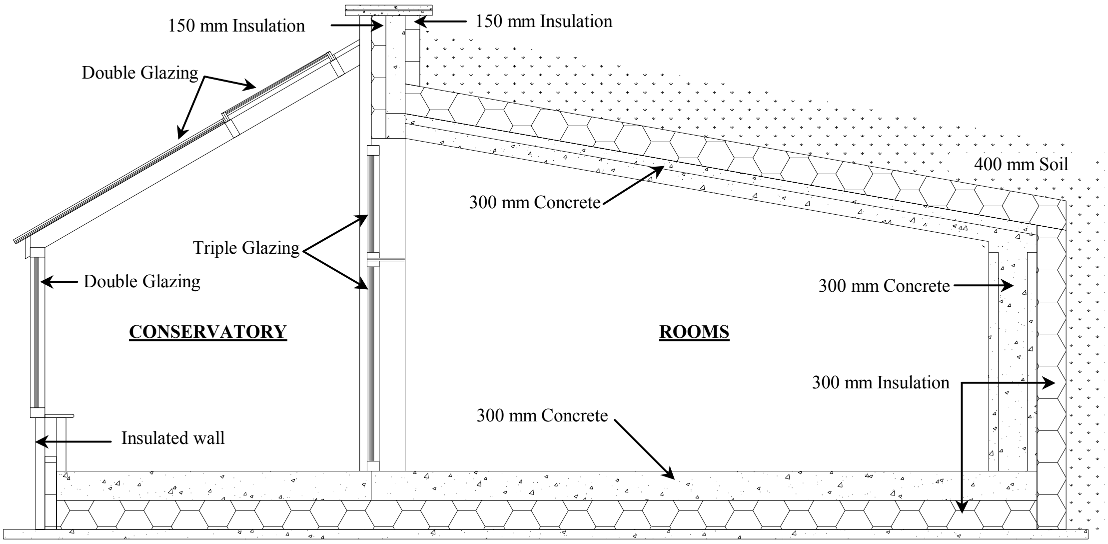

Fig. 3. Typical section of high thermal mass passive solar house

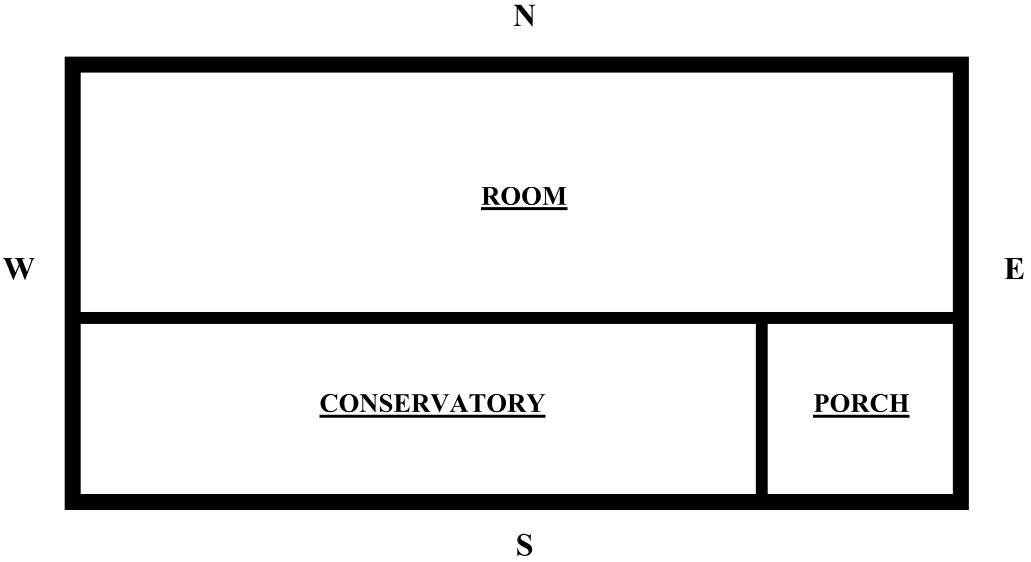

Fig. 4. Thermal zoning of the simulation model

4. Simulation results and discussion

Thermal massiveness and accuracy:

Simulations with annual weather data files are usually run to cover a period of one year starting from 1st of January to 31st of December. When mass is involved in dynamic conduction heat transfer, there is always either accumulation or depletion of heat in the mass. At the beginning of the simulation however, there is no information available about thermal accumulation or depletion in the mass. The reason is that the initial conditions required for the model governing equations are obtained from the initial steady state solution. Thus, depending on the thermal massiveness of the building, predicted zone air temperatures from the simulation may significantly differ from the actual solution (with initial thermal accumulation) for the initial period of the simulation. Further, the length of this period during which the predicted temperatures deviate is dependent on the building time constant, τ and it is defined as,

$$\tau = R_{overall} \times C_{overall} \tag{1}$$

where $R_{overall}$ is overall building envelope resistance excluding air to ground resistance in K/W and $C_{overall}$ is the overall thermal capacitance of the building in J/K.

It is to be noted that $R_{overall}$ in the above equation consists of infiltration of ambient air as well. Moreover, $R_{overall}$ is based on the difference between the mean inside and mean outside temperatures. As such, since the mean temperature of the ground is different from that of the ambient air, air to ground resistance is not included in determining $R_{overall}$. $C_{overall}$ in eq. (1) is based on the external massive walls that form the building envelope. As can be seen from eq. (1), the units of τ are seconds. Thus the larger the value of τ, the longer it takes the initial thermal accumulation in the mass into account. Further, the degree of error in the initial period of the simulation is dependent on $C_{overall}$.

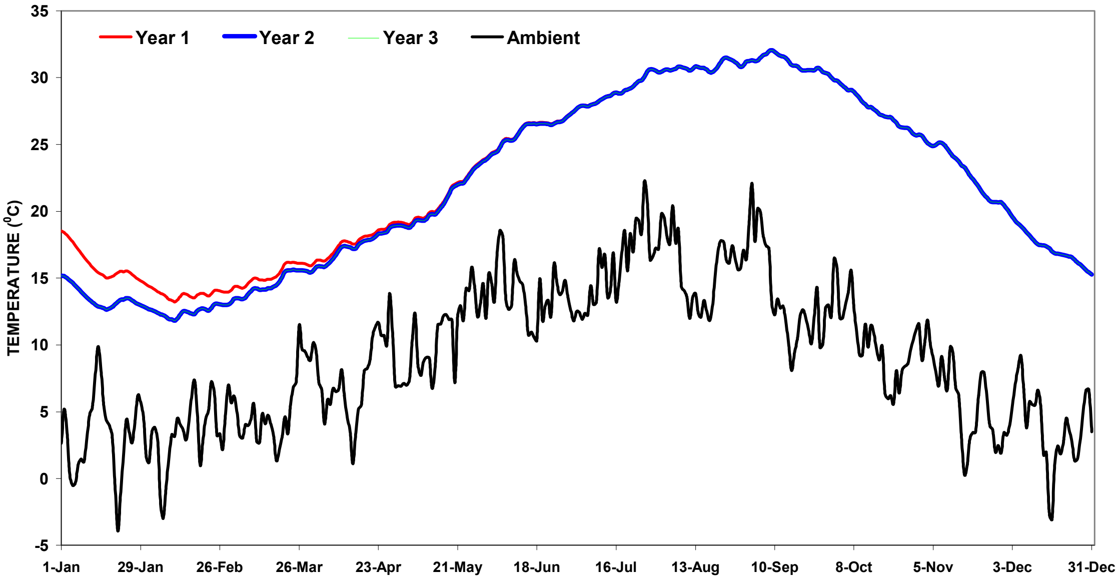

Fig. 5. Room air temperature for three years from modified EnergyPlus

Both SUNREL and EnergyPlus are not capable of simulating a period longer than a year. However, after modifying the source code of EnergyPlus it was possible to simulate the same annual weather file repeatedly over periods longer than a year. Fig. 5 shows the predicted room (see fig. 4) air temperature in the first three years obtained from modified EnergyPlus program. It can be seen from fig. 5 that the predicted temperature deviates from the actual solution for the first two and a half month period. $R_{overall}$, $C_{overall}$ and τ for the building are 0.055 K/W, 404932 kJ/K and 633.8 hours respectively and were obtained from SUNREL simulations. The effect of thermal massiveness on the accuracy of the predicted temperature in the initial period of the simulation is depicted in fig. 6. Building 1 in fig. 6 is the reference building (Hockerton high thermal mass house) and building 2 is identical to building 1 in all respects except the massiveness of the construction. All wall thicknesses of building 2 are set to be half of their counterparts in building 1. Note that reducing mass wall thicknesses results in smaller $C_{overall}$ and $R_{overall}$ of the building and hence shorter time constant, τ. $R_{overall}$, $C_{overall}$ and τ for building 2 are 0.005 K/W, 205512 kJ/K and 278 hours respectively. As can be seen from fig. 6, the initial temperature deviation in building 2 lasts only for about a month and a half. Further, the initial error in the high mass house (building 1) is relatively lower than that in building 2.

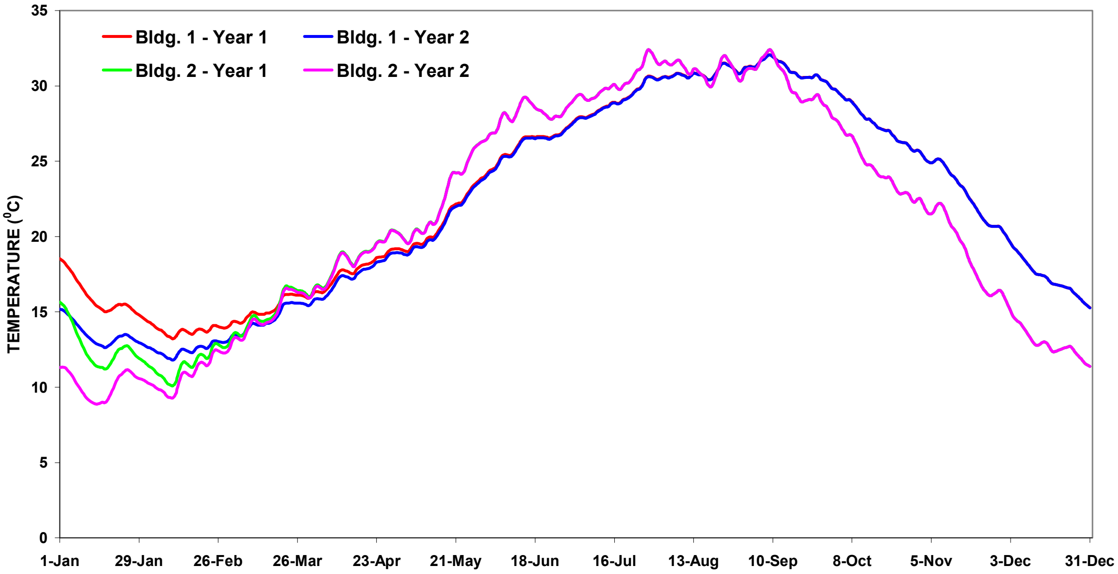

Fig. 6. Room air temperatures of buildings 1 and 2

Inter-zone solar transfer:

The predicted room annual temperature variation from SUNREL simulations is significantly different from the measured data. All the simulations were carried out with the keyword ‘area’ to ensure uniform solar distribution over interior surfaces of zones and with inside and outside surface coefficients as 10.0 and 25.0 W/m^2.K respectively. In addition to that, the inter-zone (conservatory – room) solar transfer was also held constant for the entire simulation period. However, from a number of exploratory runs it was found that the solar transfer from the conservatory to the room considerably influences the room air temperature. Further, the amount of direct beam radiation transmitted through the glazing in the partition wall changes with time. In winter months, the room receives more direct or beam solar radiation with lower solar altitude angles and vice-versa. This concept is illustrated in fig. 7. The solar transfer was therefore input as a schedule and the latter was defined as a function of monthly mean solar altitude. The schedule of solar fraction transferred from the conservatory to the room is given in table 1.

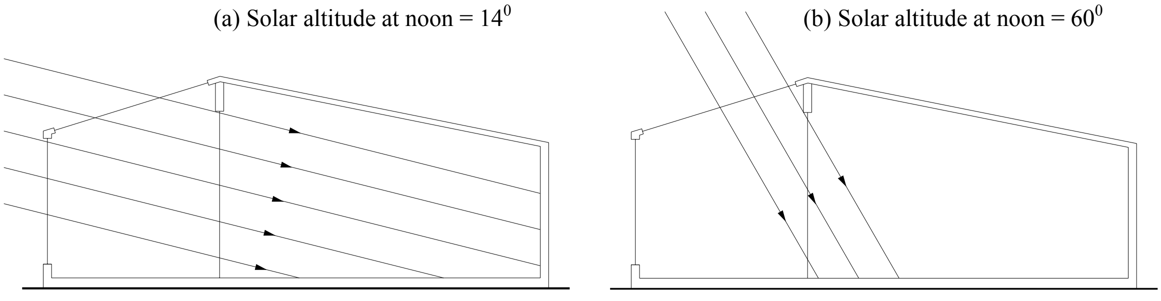

Fig. 7. Beam solar incidence (a) on January 1st (b) on July 1st

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Fraction	0.353	0.239	0.115	0.003	0.003	0.0005	0.001	0.015	0.073	0.183	0.313	0.389

Table 1. Solar transfer schedule for SUNREL

Fig. 8 shows the predicted room temperatures with the above solar transfer schedule together with fixed solar transfer fraction of 0.2 for the entire year. It was also assumed that the fractions of solar losses from the conservatory, porch and the room are 0.2, 0.05 and 0.05 respectively. Also shown in fig. 8 are the measured room temperatures from the Hockerton high thermal mass house. All the graphs in fig. 8 are based on inside and outside surface coefficients of 10 W/m^2.K and 25 W/m^2.K respectively.

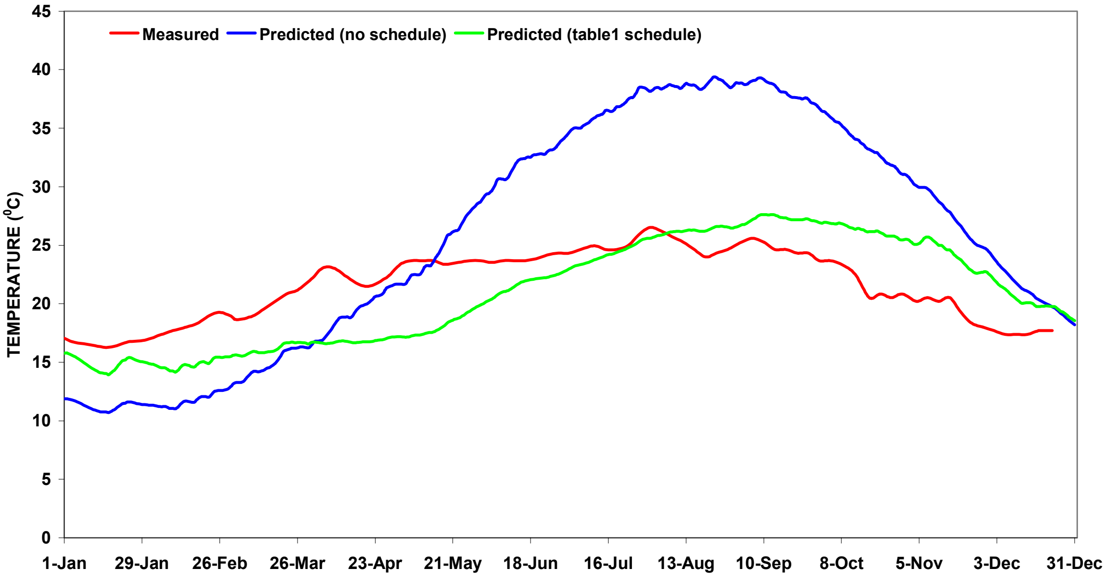

Fig. 8. Measured and predicted (SUNREL) temperatures in room

The predicted annual temperature variation of the room air from EnergyPlus is depicted in fig. 9. Also included in fig. 9 are the measured temperatures and the simulation results obtained from SUNREL. The predicted temperatures from SUNREL are based on the following conditions. The solar loss fractions for the conservatory, porch and the room are 0.1, 0.05 and 0.05 respectively. Solar fractions transferred from the conservatory to the room are defined by a schedule whose values are given in table 1. Surface to air coefficient for inside surface is taken as 10 W/m^2.K and that for the outside surfaces as 25 W/m^2.K. Solar distribution on the inside surfaces is based on the surface area using the keyword ‘area’. For EnergyPlus simulation, the surface to air coefficients are the same values used for SUNREL simulation.

As can be seen from fig. 9, EnergyPlus underestimates the room air temperature during colder months and overestimates the same during warmer months. This can be attributed to the amount of direct radiation received by the room through the transparent surface in the partition wall at different solar altitudes as shown in fig. 7. EnergyPlus inter-zone solar transfer model treats the solar radiation transferred from one zone to the other as diffuse radiation. SUNREL results in fig. 9 do not correctly represent the air temperature during the initial period. This is because the thermal accumulation in the mass is not taken into account at the beginning of the simulation. If the predicted temperature by SUNREL at the end of the simulation (Nov. – Dec.) is extrapolated, it is possible to get an approximate temperature profile at the beginning of the simulation. When the extrapolated temperature is compared with the computed temperature in the initial period, it can be seen that the latter is less than the actual temperature. In contrast, the computed temperature without the initial thermal accumulation from EnergyPlus is higher than the actual temperature (fig. 5). This could be due to the fact that SUNREL and EnergyPlus employ two different solution methods for transient conduction.

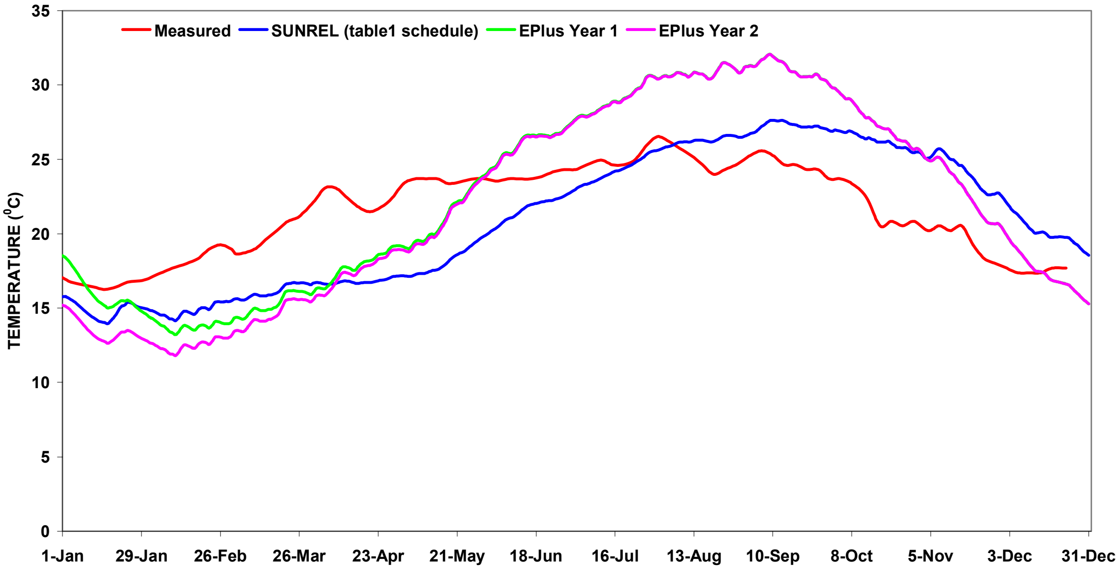

Fig. 9. Predicted room air temperatures from SUNREL and EPlus with measured data

5. Conclusion

Use of building energy simulation software for predicting thermal behaviour of a high thermal mass passive solar house was investigated. Two such software, SUNREL and EnergyPlus have been used for the study. Accurate estimation of the solar radiation transmitted to various zones in the building is a crucial factor for the overall accuracy of the predicted air temperatures. EnergyPlus treats the solar transmitted to the interior zones as diffuse radiation although these zones may receive direct or beam radiation. This may underestimate the solar radiation transmitted during colder months and overestimate during warmer months. SUNREL on the other hand needs user defined solar transfer fractions for inter zone transfers. The user is therefore expected to input these values preferably as a schedule taking the angle of incidence and the glazing area into account. The initial part of the simulation results deviate from the actual solution due to the unaccounted thermal accumulation. The length of this initial period depends on the massiveness of the building.

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