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Performance Evaluation of a Solar Passive Cooling System Constituting Experimental Composite Roof Insulation by Dynamic Computer Simulation

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Abstract: The paper presents thermal performance of a Solar Passive Cooling System (SPCS) evaluated by dynamic computer simulation. A state of the art computer simulation program has been used to evaluate thermal performance of various types of building as different Solar Passive Cooling Systems (SPCS) are applied on them. Experimental results of such simulations are well accepted by the research community as the simulation programs are validated by field results The numerical evaluation was done by the dynamic computer simulation program 'A-Tas' (version 8.30) The SPCS discussed was composed of a number of materials forming composite roof insulation; while the performance evaluation was conducted taking into account the local climatic condition of Dhaka, a Tropical city in Bangladesh. Accordingly, a weather file for Dhaka was created for this study with the assistance of Environment Design Solution Ltd. (EDSL), Milton Keynes, UK. As the aim of this investigation was to study the thermal performance of an alternative roof insulation, therefore an un-insulated roof was considered as a base case to which experimental insulation could be applied and compared. In the evaluation process certain environmental criteria that are directly influenced by roof insulation were considered.

Keywords: Computer simulation, Roof insulation, Thermal performance, Passive cooling.

Introduction

Thermal performance of roof insulation and its mpact on indoor environment can be studied discretely by dynamic simulation. Because in reality, due to the synergistic effect of various factors it is difficult to isolate the effect of a single aspect or an element, or the changes in it. Thermal simulation allows study of the effect in one aspect keeping other factors constant. The observations of simulated thermal behavior that occur due to the changing parameters allow the identification of elements, the modification or introduction as they relate to indoor comfort. Furthermore, this approach helps in specifying the effective option of insulation parameter among a wide variety of combinations which would otherwise be very time consuming and cumbersome to work with in real life situation. Another significant advantage of this simulation study is possibility of analyzing thermal performance of operable roof insulation for any period of the year simply by assigning simulation parameters (like temperature, radiation, wind speed and direction relative humidity cloud cover). A dynamic computer simulation program named A-Tas (version 8.30) has been used for this simulation study.

Different investigations using solar passive cooling systems (SPCS) have been experimented previously. Among some of the important investigations, Almao de Herrera and Rincon (1993) have numerically proved the effectiveness of SPCS in the form of roof pond to reduce the thermal load. Although the concept of roof pond was first introduced by Hay and Yellot (1978) while Clark and Allen (1981), Clark (1989) and Sodha et al (1981) have carried out further experimental and commercial application of this technique. Givoni (1981) and Gonzalez (1991) have tested the performance of massive roof and roof pond radiator with operable insulation as SPCS. Later Givoni (1994) has reported the effectiveness of fixed shade or floating insulation roof pond system under different climatic conditions. Experimental comparisons of radiant cooling obtained by a gray-body emitter and a selective emitter have been done by Mitchell (1976), and Landro and Mc Cormic (1980) in Australia. Shirish Patel & Associates Consultants Private Limited in India developed double corrugated sheets as SPCS. In Bangladesh some attempts of SPCS were made on the roof to improve indoor thermal performance e.g. with inverted earthen pots (Mallick, 1993), hollow tiles (Imamuddin et al. 1993) and operable insulation membrane made of Styrofoam sandwiched between Polyvinyl Chloride (PVC) sheet (Mridha, 2002) over concrete roof.

In this work an SPCS base on cooling of thermal mass by reducing the incident solar radiation on rooftop composed of composite insulating materials has been selected as one of the viable alternatives to be to be analyzed by computer simulation.

Conduction in the fabric of the building is treated dynamically using a normal co-ordinate method1. The computational procedure calculates conductive heat flows at the surfaces of walls and other building elements as functions of the temperature histories at those surfaces.

Constructions of up to 12 layers may be treated, where each layer may be composed of an opaque material, a transparent material or a gas. Convection at building surfaces is treated using a combination of empirical and theoretical relationships relating convective heat flow to temperature difference, surface orientation, and, in the case of external convection, wind speed. Long-wave radiation exchange is modelled using the Stefan-Boltzmann law, using surface emissivities from the materials database. Long-wave radiation from the sky and the ground is treated using empirical relationships. Solar radiation absorbed, reflected and transmitted by each element of the building are computed from solar data on the weather file. The calculation entails resolving the radiation into direct and diffuse components and calculating the incident fluxes using knowledge of sun position and empirical models of sky radiation. Absorption, reflection and transmission are then computed from the thermo-physical properties of the building elements. External shading and the tracking of sun patches around room surfaces may be included at the user's option.

1 Time-varying conduction heat transfer and heat storage in the building fabric is modeled in A-Tas using the normal co-ordinate method with a time-step of 1 hour. The method is closely related to methods based on Response Factors and Conduction Transfer Functions but offers substantial run-time and storage savings relative to these methods. (For further reading please see the conduction algorithm section of A-Tas Theory manual).

Overview of the Simulation Program

A-Tas is a program, that simulates the thermal performance of buildings. The main applications of the program are assessment of environmental performance, natural ventilation analysis, prediction of energy consumption, plant sizing, analysis of energy conservation options, and energy targeting.

A-Tas is linked to the 3D modeller and 3D-Tas. Together. these two programs go by the name Tas Lite. The fundamental approach adopted by A-Tas is dynamic simulation. This technique traces the thermal state of the building through a series of hourly snapshots, providing the user with a detailed picture of the way the building will perform, not only under extreme design conditions, but also throughout a typical year. This approach allows the influences of the numerous thermal processes occurring in the building, their timing, location and interaction to be properly accounted for. These processes are illustrated schematically in Figure 1, which shows the transfer of heat in various methods as it is conveyed into, out of and around the building by a variety of heat transfer mechanisms.

Thermal Simulation Study

Test Room Modelling

The criteria for site and building selection were based on the following factors:

- The site should be in urban context and should have characteristics typical of the general urban fabric of Dhaka city.
- Test Room should have an exposed roof; preferably a single storied building or should be located on the top floor of a multistoried building.

According to the above criteria, the Test Room on the top floor of a 4-storied building was selected at Monipuri Para (near national assembly building.) The

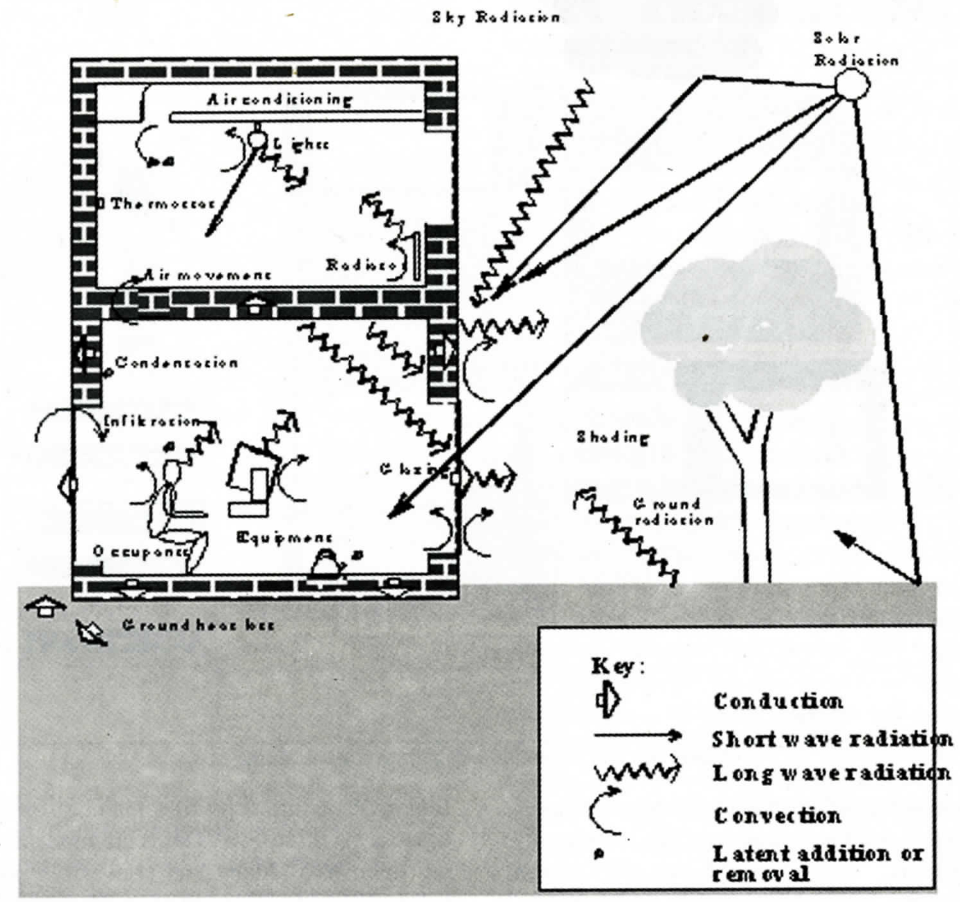

Figure 1 : Schematic Representative of Heat Transfer mechanism in a building (After A-Tas) .

Test Room dimensions are 4.19 m × 3.68 m. located at the northeast corner of the site in which north and east walls are exterior walls, while south and west are blocked by other functions. Actually the Test Room is a part of a complete residence with other bedrooms, living room, dining, kitchen, toilets etc. but they are ignored to simplify the simulation operation. Only the functions (identified as zone) that have direct bearing to the Test Room are considered for Test Room modeling in simulation program (Figure 2).

Period of observation was in the months of April 2000, representing pre-monsoon and the general climate during this period is hot-dry (Ahmed, 1995; Mallick, 1994), and is characterized by low humidity and low cloud cover, high temperature,high radiation. In pre-monsoon period due to high values of temperature and solar radiation, comfort level of the indoor environment is considerably reduced. Therefore, it was possible to critically evaluate the thermal performance of the SPCS during this period when the climatic values responsible for creating discomfort are significantly high.

Preparation of Databases

The A-Tas databases contain data, which is regularly required for building model preparation and evaluation. There are databases of i) Climate ii) Internal Conditions iii) Materials and iv) Constructions. Climate and internal database have to be prepared on the basis of site parameters and Test Room condition while Materials and Construction database are built-in the program and can be arranged in different combinations.

Climate

The Climate database stores files containing hourly weather data. The weather files supplied with A-Tas cover different regions of the world and each represents a typical year's weather for the region in question. The name of each weather file is prefixed with a country identifier (for example 'Ban_' for Bangladesh) and options are there to allow creating specific weather files and can be added to the Climate database. A weather file consists of a group of

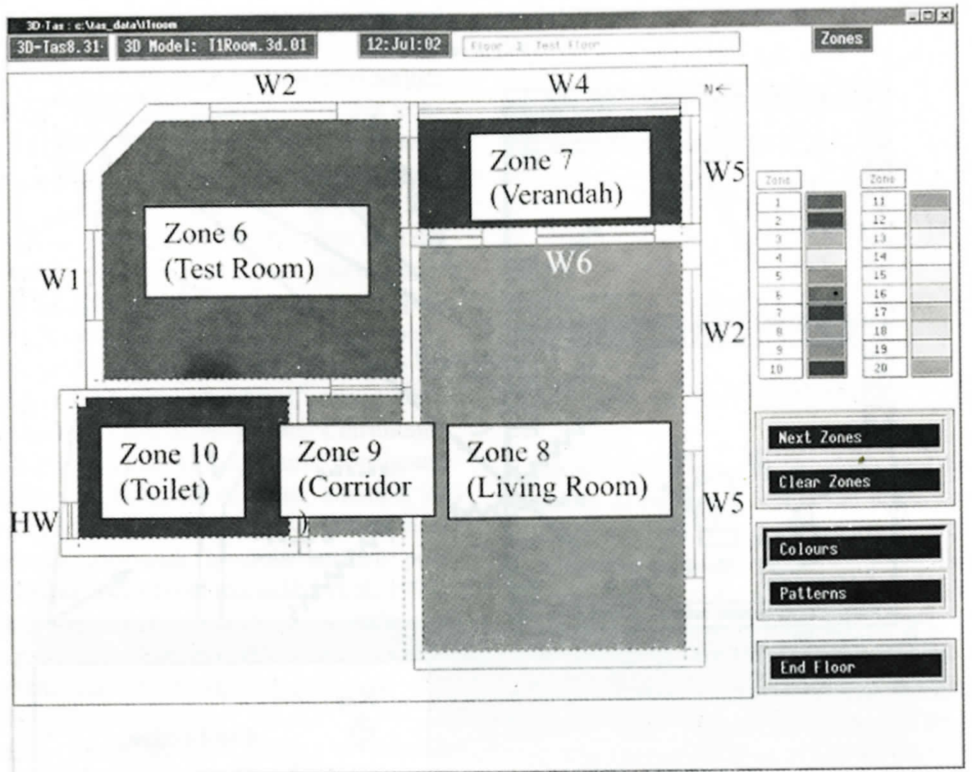

Figure 2 : Test Room modeling for simulation study.

parameters relating to the weather of a site and hourly values of seven weather variables. The weather file 'Ban_Dhaka.wfl' was prepared for the present research purpose, where three-hourly weather data2 was collected from Climate Division, Bangladesh Meteorological Department Agargaon, Dhaka. As per simulation program requirements all three-hourly data was converted to hourly data by interpolation method.

The site parameters of weather file are as follows:

The combination of site parameters and hourly weather variables forms the weather file, with which the simulation program (A-Tas) is able to analyse any climatic characteristics of the particular site.

Test Room Conditions

Internal conditions of the Test Room include heat gains from lights, equipment and occupants as well as infiltration3 rates and plant operation (for mechanical ventilation) specifications are grouped together in profiles, which are applied to the various zones of the building (please also see Table 2 for more detail). Internal Conditions profiles may be stored in a database for later retrieval. Gains are modelled by resolving them into radiant and convective portions. The

Parameters	Details
Latitude (degrees North)	23Deg. 46mt. N
Longitude (degrees E)	90 Deg. 23 mts. E
Time Zone (hours ahead of GMT)	GMT + 06.00
Ground Temperatures (deg. C)	25.8 degrees Celsius

convective portion is injected into the zone air, whilst the radiant gains are distributed amongst the zone's surfaces. Infiltration, ventilation and air movement between the various zones of the building causes a transfer of heat between the appropriate air masses which is represented by terms involving the mass flow, the temperature difference and the heat capacity of air. A-Tas offers the capability to calculate natural ventilation airflows arising from wind and stack pressures. Solar radiation received by an opaque surface can be partially absorbed and partially reflected and while entering a zone through transparent building components radiation on internal surfaces may be absorbed, reflected or transmitted depending on the surface properties. Distribution of reflected and transmitted solar radiation continues until all the radiation has been accounted for. A-Tas solves the sensible heat balance for an enclosed zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. This procedure is repeated for each hour of the simulation. A latent balance4 can also be performed for each zone, which takes account of latent gains, moisture transfer by air movement and the operation of humidification and dehumidification plant when air-conditioning system is installed in a room.

2 Hourly climatic data of global and diffused solar radiation, cloud cover, DBT, RH, wind speed and direction for the year 2000 was sent to the product support manager of Environmental Design Solution Limited (EDSL) and their programmers developed this weather file for this specific research.

3 The term 'infiltration' is used in A Tas to describe the user-specified exchange of air between a building zone and the exterior by natural ventilation. Infiltration carries both sensible and latent heat into or out of the zone. Infiltration rates for each A-Tas zone may be specified, and scheduled to vary with time, by setting air change rates in Internal Conditions.

Materials

The Materials Database stores data on the thermo physical properties of building materials. Data on a wide selection of materials is supplied with the A-Tas program. Materials are used as constituents for construction types in the Constructions Database. Each material is identified by a material code, which consists of two parts: the material category and the item number. The material category is characterized identifying a class of materials (for example insulating materials). The item number is an integer, which identifies an individual material within the category.

Constructions

The Constructions Database stores construction types for walls, floors, etc. built up from layers composed of materials from the materials database. No set of constructions are supplied with the A-Tas program; it has to be created with the help of construction database and material database.

Each construction type is identified by a construction code (C-Code), which consists of two parts: the construction category and the item number. The construction category is a name identifying a class of construction types. The item number is an integer that identifies an individual construction type within the category. The two parts of the C-Code are separated by a slash (/). The construction category starts with a letter; thereafter it may contain letters, digits, blanks and the underscore character '_'. (e.g. the construction code for the composite insulation is 'ceiling/5. That means the simulation program will consider this composite insulation as a category of ceiling whose type is 5) Table 3 is the database of creating material attributes. Columns for 'M-code and material name' and 'width' of that material have to be filled up by the user and the simulation program will make all other calculations. The particular SPCS in the form of composite insulation was created by specifying all the materials used and their width in the construction database and (Table 3) a representative diagram is shown in Figure 3.

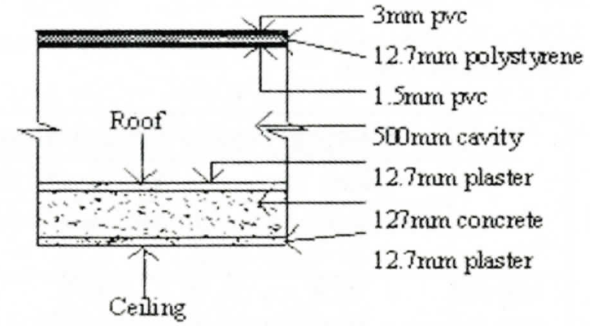

Figure 3 : Construction detail of composite insulation

Discussion of Results: Thermal Performance of Roof Insulation

Simulation study was performed in the Test Room, with insulation for the month of April, which falls in pre-monsoon or hot-dry period. Diurnal variation in temperature is most pronounced during this season. In the case of Dhaka it is evident from solar radiation and atmospheric clearness data that during this month high radiation influx is the major factor contributing to the difference in temperature observed. Thus it is the most critical among all other months of the year and hence chosen for investigation. Significant findings (Table 1) of environmental condition of the Test Room are discussed here to evaluate thermal performance of the roof insulation. The aim of this investigation is to study the thermal performance of roof insulation, therefore uninsulated roof has been considered as a base case to which insulation on roof was compared. In the evaluation process two significant environmental criteria like Mean Radiant Temperature (MRT) and Ceiling Temperature (CT) as the result of incident solar radiation in the Test Room, which are directly influenced by roof insulation, have been considered. Discussion consists of statistical and synoptical considerations.

4 No control band is specified for humidity control at this stage of problem analysis as no mechanical ventilation system was installed in the Test Room therefore no moisture content was considered.

Table 1: Hourly average and three hourly moving average ceiling and mean radiant temperature generated by the simulation program

Time	Average Hourly Temperature				3 Hourly Moving Average			
	Ceiling Temp.		Mean Radiant Temp.		Ceiling Temp.		Mean Radiant Temp.	
	Base Case	Insulated Roof	Base Case	Insulated Roof	Base Case	Insulated Roof	Base Case Roof	Insulated Roof
1:00 AM	35.9	31.1	35.1	29.9				
2:00 AM	35.2	30.8	34.6	29.5	35.2	30.8	34.7	29.6
3:00 AM	34.5	30.6	34.3	29.5	34.5	30.6	34.3	29.4
4:00 AM	33.8	30.4	33.9	29.3	33.9	30.4	33.9	29.3
5:00 AM	33.3	30.2	33.5	29.1	33.3	30.2	33.6	29.1
6:00 AM	32.8	30.0	33.2	28.9	32.8	30.1	33.5	29.3
7:00 AM	32.5	30.0	33.7	30.1	32.7	30.1	34.2	30.0
8:00 AM	32.8	30.3	35.7	31.1	33.0	30.4	35.3	31.3
9:00 AM	33.6	30.7	36.4	32.8	33.8	30.7	36.4	32.0
10:00 AM	34.9	30.9	36.9	31.9	35.0	30.9	36.8	32.0
11:00 AM	36.4	31.1	37.1	31.3	36.4	31.1	37.1	31.2
12:00 PM	38.0	31.2	37.3	30.5	38.0	31.2	37.3	31.0
1:00 PM	39.4	31.3	37.6	31.1	39.4	31.4	37.8	31.1
2:00 PM	40.6	31.6	38.4	31.6	40.6	31.6	38.2	31.5
3:00 PM	41.7	31.8	38.6	31.8	41.5	31.8	38.7	31.7
4:00 PM	42.4	32.0	38.9	31.8	42.3	31.9	39.1	31.5
5:00 PM	42.8	32.0	39.6	31.0	42.6	31.9	38.9	31.1
6:00 PM	42.7	31.8	38.1	30.6	42.5	31.8	38.2	30.7
7:00 PM	41.9	31.7	37.0	30.4	41.7	31.7	37.4	30.4
8:00 PM	40.6	31.5	37.0	30.3	40.6	31.5	36.9	30.3
9:00 PM	39.3	31.3	36.6	30.1	39.4	31.3	36.6	30.1
10:00 PM	38.2	31.1	36.1	29.9	38.2	31.1	36.1	30.0
11:00 PM	37.1	30.9	35.6	29.8	37.2	30.9	35.6	29.8
12:00 AM	36.2	30.7	35.2	29.6				
Average	**37.4**	**31.0**	**36.3**	**30.5**	**37.5**	**31.1**	**36.4**	**30.6**

Statistical Analysis

Standard Deviation

The standard deviation is more stable than any other means of description and is, therefore, least disturbed by sampling fluctuations. It provides a tangible basis of comparing two sets of data in terms of the extent of their variability and uniformity. Standard deviation can be obtained from following formula:

$$STDV(s) = \sqrt{\frac{\sum (x-\bar{x})^2}{n}}$$

s is quite useful because any continuous distribution can be described in terms of standard deviation units. By taking the square root, the variance of a distribution is converted to a standard form so that 1 standard deviation unit equals s, 2 units equals 2s and 3 unit equals 3s (Kurtz, 1983).

Thus for

$CT_{(uninsulated)}$: s = 3.52; 2s = 2(3.52) = 7.04; 3s = 3(3.52) = 10.56

$CT_{(insulated)}$: s = .59; 2s = 2(.59) = 1.18; 3s = 3(.59) = 1.77

where

s = Standard deviation of temperature in °C

x = individual hourly values (temperature in °C)

$\bar{x}$ = the arithmetic mean (mean temperature in °C)

n = the number of items (hour) = 24

$CT_{(uninsulated)}$= Ceiling temperature of Test Room with uninsulated roof in °C

$CT_{(insulated)}$= Ceiling temperature of Test Room with insulated roof in °C

Moreover if the frequency polygon of a distribution is bell shaped in form, then 68% of all the observations are located in the area from 1 standard deviation unit below the mean to 1 standard deviation unit above the mean, 95% are 2 units and 99% are 3 standard deviation units below and above the mean (Kurtz, 1983).

The utility of standard deviation can be used in the simulation study to analyze the generation of ceiling and mean radiant temperature in the case of uninsulated and insulated roof. Following interpretation of the results can be made:

For Base Case (CT uninsulated):

- $CT_{(uninsulated)}$ for instance, with a standard deviation of 3.52 will maintain a temperature somewhere between ±3.52 °C above and below the mean temperature of 37.4 °C (Table 1). That means 68% of the time generated data will be somewhere between 33.88 °C to 40.92 °C (37.4-3.52=33.88 °C and 37.4+3.52=40.92 °C).
- 95% of the time, the temperature reading will range 2 (3.52) °C around the mean or the temperature plots will be between 30.36 °C to 44.44 °C
- 99% of the time the temperature range will be 3(3.52) or from 26.84 °C to 47.60 °C.

So large standard deviation of CT (uninsulated) results in much wider range of temperature fluctuation.

For SPCS ($CT_{insulated}$)

- while in the case of $CT_{(insulated)}$ with a standard deviation of .59 will maintain a temperature somewhere between ±. 59 °C above and below the mean temperature of 31.0 °C (Table 1). That means 68% of the time generated data will be somewhere between 30.41 °C to 31.59 °C (31-.59=30.41 °C and 31+. 59=31.59 °C).
- 95% of the time, the temperature reading will range 2 (.59) °C around the mean or the temperature plotting will be between 29.82 °C to 32.18 °C.
- 99% of the time the temperature range will be 3(.59) or from 29.23 °C to 32.77 °C.

Therefore it is easier to predict the temperature profile of $CT_{(insulated)}$ with narrow boundaries, while it is difficult to make any meaningful prediction for $CT_{(uninsulated)}$. The same inference can be drawn for $MRT_{(insulated)}$ and $MRT_{(uninsulated)}$; the former is more predictable than the latter.

t-Test

To test the significance of difference between two sample means, temperature profile of CT and MRT of uninsulated and insulated roof have been considered as samples. Here in these cases comparison are made between values of t obtained from the sample with the theoretical values of t at 5% level of significance for (n_1+n_2-2) degrees of freedom. The governing equation is:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where

$$s = \frac{\sum (x_1 - \bar{x}_1)^2 + (x_2 + \bar{x}_2)^2}{n_1 + n_2 - 2}$$

x_1 = individual hourly temperature values in °C (for $CT_{uninsulated}$ and $MRT_{uninsulated}$)

x_2 = individual hourly temperature values in °C (for $CT_{insulated}$ and $MRT_{insulated}$)

$\bar{x}_1$ = the mean temperature of first sample in °C (for $CT_{uninsulated}$ and $MRT_{uninsulated}$) $\bar{x}_2$ = the mean temperature of second sample in °C (for $CT_{insulated}$ and $MRT_{insulated}$)

n_1 = the size of the first sample (hours) = 24

n_2 = the size of the second sample (hours) = 24

df = degrees of freedom, the number of values free to vary in a distribution without changing the sum of the distribution. Here in this case as 24 data were generated for each sample (hourly temperature values) so df will be (24+24-2)=46

Therefore test of significance between $CT_{(uninsulated)}$ and $CT_{(insulated)}$ is obtained from the above equation as: $t = 3.464$ and between $MRT_{(uninsulated)}$ and $MRT_{(insulated)}$ as $t = 17.85$

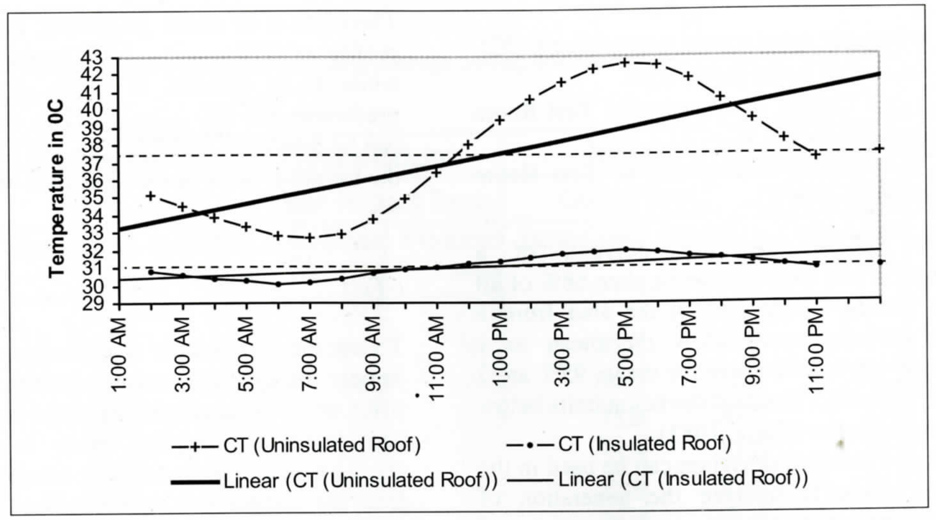

Figure 4 : Comparison of three hourly moving average plots of ceiling temperature for uninsulated and insulated roof of the Test Room showing linear trend line and mean value line.

The theoretical value of t for 46 degree of freedom at 5% level of significance is approximately 2.021 (Mian and Miyan, 1994). It is approximate, because no table value appears for df=46. In this case the value for the next lowest df, which is in this case 40 has been used (The value of df=46 would actually be less than 2.021). Since the observed value of t (as 3.464 and 17.85) is higher than the theoretical value, therefore both the observed temperature difference of between CT $_{(uninsulated)}$ and CT $_{(insulated)}$ and MRT $_{(uninsulated)}$ and MRT $_{(insulated)}$ is significant. It suggests that, a substantial amount temperature variation occurs when the SPCS in the form of composite insulation is considered over the roof of the Test Room according to generated data by the simulation program. Therefore the numerical values of temperature in insulated situation are lower and more close to comfortable temperature range for Dhaka.

Times Series

Graphical plots of the 24 hours time series (3 hourly moving average) of temperature data of CT and MRT of the Test Room without and with insulation are illustrated in Figure 4 and 5. The former figure expresses that the value of CT $_{(uninsulated)}$ ranges from 32.7 °C to 42.6 °C with average of 37.5 °C and CT $_{(insulated)}$ ranges from 30.1 °C to 31.9 °C with average of 31.1 °C. Similarly Figure 5 illustrates the value of MRT $_{(uninsulated)}$ ranges from 33.5 °C to 39.1 °C with average of 36.4 °C and MRT $_{(insulated)}$ ranges from 29.1 °C to 32.0 °C with average of 30.6 °C. For both instances temperature profiles are almost similar to average hourly temperature profile (Figure 6). When the roof is not insulated trend line for both CT and MRT are much steeper than insulated situation and temperature plots are significantly higher during afternoon hours.

Synoptical Observations

As the ceiling is closely associated with the roof and also due to its physical positioning, any temperature fluctuation on roof directly and immediately affects ceiling temperature. A warm ceiling increases indoor temperature of the room below by the process of convection and radiation; therefore, it is a significant factor to be considered in the evaluation.

Results of hourly average simulation study conducted during 23-25 April 2000 and the corresponding numerical results are presented in Table 1. According to the supplied data by Agargaon Meteorological office, the average wind velocity during observation period was 1.2 m/s while the maximum and minimum DBT was 33.2 °C and 21.2 °C respectively. Relative humidity varied from 45-96%. The measured hourly average values of these climatic variables are used as input data by 'A-Tas'.

In Figure 6 hourly average ceiling and mean radiant temperatures for uninsulated and insulated roof of the test cell are shown. It can be observed that the trend of simulation curve for ceiling temperature of uninsulated roof is a prominent sinusoidal curve where minimum temperature is 32.5 °C generated at 7 AM while the maximum is 42.8 °C at 5 PM. thus the max.-

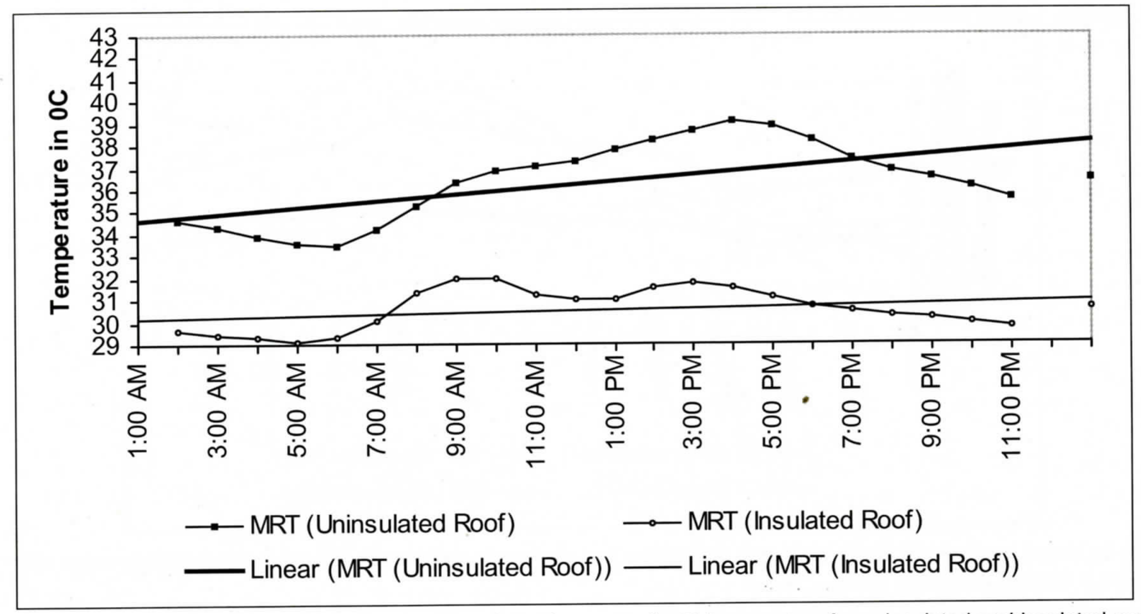

Figure 5 : Comparison of 3 hourly moving average plots of mean radiant1 temperature for uninsulated and insulated roof of the Test Room showing linear trend line and mean value line.

min. difference becomes 10.3 °K. Considering the composite insulation as SPCS over the test cell; the simulated numerical values illustrate a different picture. The curvature of temperature profile is almost flattened where the maximum fluctuation of temperature is only 2 °K. The maximum and minimum ceiling temperature in the Test Room with insulated roof are 32.0 °C and 30.0 °C respectively. The maximum ceiling temperature deviation between uninsulated and insulated ceiling of the Test Room is 10.8 °K (25%). The significant temperature variation between CT (uninsulated) and CT (insulated) is observed between 11 AM to 11 PM.

MRT is an important factor to be considered in thermal performance evaluation. It includes the effect of incident solar radiation and has as great an influence as air temperature.

Simulation curves of MRT with respect to uninsulated and insulated roof of the test cell are a bit different from curves of the CT. Latter curves are smoother than the former. We can observe certain arbitrary temperature fluctuations in MRT profiles. MRT $_{(uninsulated)}$ reaches its peak (39.6 °C) at 5 PM while the lowest (33.2 °C) is observed at 6 Am. In the case of MRT $_{(insulated)}$ simulation data illustrates the highest temperature value (32.8 °C) at 9 AM while the lowest (28.9 °C) was attained just 3 hours previously. The variance between MRT $_{(uninsulated\ maximum)}$ and MRT $_{(insulated\ maximum)}$ is 6.8 °K (17%). The significant temperature variation between MRT $_{(uninsulated)}$ and MRT $_{(insulated)}$ is observed between 8 AM to 8 PM. Additionally, Figure 4 also shows that the time lag of CT $_{(uninsulated)}$ relating to CT (insulated) is 10 h while time lag of MRT $_{(uninsulated)}$ with respect to MRT $_{(insulated)}$ is 8h.

Comfort Zone Analysis

The exterior of the building envelope is alternately heated during day and cooled at night. Part of the heat absorbed during the day warms the mass of the building and a part is transmitted to the interior. The ratio between the heat absorbed and stored in the materials depends mainly on the heat capacity of the envelope. During the summer and in warm regions, the external surface (particularly roof) temperatures are above the internal level (e.g. Ceiling) during day and below it at night. Here, in addition to its quantitative damping effect on heat exchange, the temperature of ceiling may also have an influence on the direction of heat flow thus on Comfort level. Therefore MRT and also CT were considered for comfort zone analysis.

Comfort zone is based on indoor air temperature, relative humidity and airflow, particularly devised for summer comfort. In still air condition, the boundary conditions for air temperature are between 24-32 °C and upper limit is increased to slightly over 34 °C with .3m/s air speed and nearly 36 °C with .45 m/s air speed (Mallick, 1994). After superimposing summer comfort zone on the Figure 6 certain thermal information can be traced out. According to the simulated curve of ceiling and mean radiant temperature in the base case of uninsulated roof all values are plotted

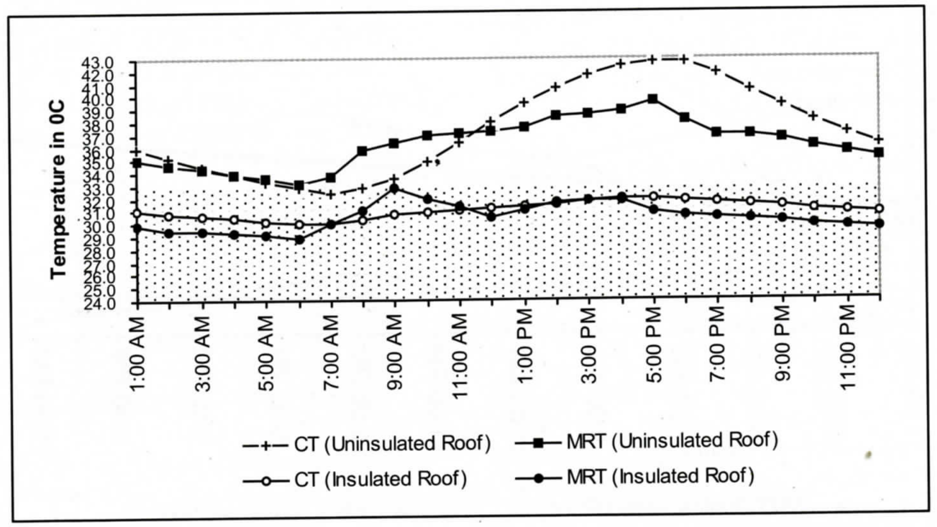

Figure 6 : Hourly temperature profile of CT and MTR of the Test Room with and without roof insulation (comfort zone in still air condition is overlaid in gray)

above the upper limit of the comfort zone in still air condition. While with insulated roof all temperature plotting (except maximum MRT of insulated roof) are within the boundaries of the comfort zone as 100% for CT $_{(insulated)}$ and 95.83% for MRT $_{(insulated)}$. and MTR of the Test Room with and without roof insulation and also temperature plotting with respect to comfort zone in still air condition.

Cooling Potential

Another important parameter to be evaluated is the mean cooling potential (MCP) of the passive system. The parameter was calculated using an experimental value of the global steady state heat transfer coefficient (UA), obtained by Gonzalez (1997, as cited by Rincon et al., 2001) in this simulation study. The UA value is 73.6 W/K and it is based on the external surface convection-radiation heat transfer coefficients. Thus using this value and the difference between daily average uninsulated and insulated ceiling temperature, the mean cooling potential per unit area of the SPCS is estimated for CT as:

$$MCP = (UA)(CT_{uninsulated} \quad CT_{insulated}) \quad A_{roof}$$
$$(73.6)(37.4\text{-}31.0)/15.25$$
$$= 30.88\ W/m^2\ K$$

---

[4] Power is always expressed in units of energy divided by units of time. Two units of power are the horsepower and the watt. One horsepower is equal to the amount of power required to lift 33,000 pounds a distance of 1 foot in 1 minute. One watt equals the power needed to do 1 joule (a joule is a unit of energy equal to 0.239 calorie) of work per second. There are 746 watts in 1 horsepower, while 1 ton of refrigeration is equals to 3516 watt.

In terms of daily removal of heat, this value of cooling potential turns out to be 741 W4h/m^2 day. While for MRT the mean cooling potential per unit area of the SPCS is estimated for MRT will be: =(73.6)(36.3-30.5)/15.25= 27.99W/m^2 K. The daily removal of heat would be 671.81Wh/m^2 day.

Conclusion

The intention of this research work was to provide an introduction for thermally responsive architecture on the basis of thermal performance of a specific SPCS. In order to arrive at some reasonable conclusion and recommendation regarding thermal performance of a solar passive cooling system considering a composite roof insulation in Dhaka, it was necessary to consider how environmental conditions of the Test Room is influenced by the application of the particular SPCS and compare with the base case (Test Room without roof insulation). The following conclusions and recommendations can be made:

- According to the temperature variation that recorded between MRT (uninsulated max.) vs MRT (insulated max.) and CT (uninsulated max.) vs CT (insulated max). , it is possible to reduce 17% thermal load through the introduction of the specified composite insulation for MRT while 25% for CT as compared to uninsulated situation.
- The average cooling potential of the studied SPCS numerically obtained is 30.88 W/m2 K for CT and 27.99W/m2 K for MRT, which in terms of daily removal of heat turn out to be 741 Wh/m2 (CT) and 671.81Wh/m2 (MRT)
- 95.83% of the data generated by computer simulation for MRT (insulated) and 100% CT (insulated) data were within the comfortable range when plotted to summer comfort zone (in still air condition).

- The mean temperature variation between MRT (uninsulated) and MRT (insulated) was observed as 5.8 K while between CT (uninsulated) and CT (insulated) the mean temperature variation was
- 6.4 K.
  Thermal time lag for CT (uninsulated) with respect to CT (uninsulated) is 10 hours and MRT (uninsulated) with respect to MRT $^{(insulated)}$ is 8 hours.

Therefore numerical values of above-mentioned findings show that the thermal simulation program can be used to investigate the effect of certain changes in the internal thermal environment of a room. It is quite clear and understandable that a much better thermal condition prevails in the Test Room when simulation study was done with the introduction of insulation over the roof of the Test Room. It actually cuts down the effect of sol-air-temperature on the roof, which is the main source of heat gain in Dhaka. Walls and windows (through which solar radiation penetrates inside the room) do not contribute towards heat gain as much as through roof. This is particularly true for single storied buildings and top floor of multistoried buildings. Moreover mean radiant temperature is reduced with roof insulation leading to a thermally agreeable condition. Thus based on the results of the dynamic simulation the performance of the roof insulation can be regarded as beneficial.

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Table 2: Internal Conditions of the Test Room as considered by the simulation program (program output)

```
 Building Name:  T1Room                    Building Data
File:   T1Room.bdf.01             Revision: 81
  Time: 23:45:28  Date: 23:Mar:02
Program:   A-Tas 8.31

 | Zone                                | Day type  |     IC -
Code    |      Internal Conditions Description                |

 |  Test Room
 |   6. Test Room                     | W+S+S DAY |   room    /
1 |                                                |

  | Temp.      | Temp.      | Prop'l    | On-off      | Humidity |
Humidity |  Plant Max.  | Plant Off |
  | Upper     | Lower      | Control | Control    | Upper    |
Lower     | Outside    | Outside  |
  | Limit     | Limit      |                        | Limit    |
Limit     | Temp.       | Temp.     |              |Include solar|
  | (deg C)  | (deg C)  | (deg C) | (deg C)  | (%)          |
(%)        | (deg C)    | (deg C)   |             |in MRT (y/n)?|
 |---------|---------|---------|----------|----------|--
--------|-----------|-----------|          |-------------|
 |    0.0   |    0.0   |    0.0   |    0.0   |    0.0      |
0.0    |   0.0       |   0.0      |          |    Yes        |

| View         |
|  Operating   | Time Plant  | Time Plant  |    Heating
|  Cooling     |             | Prop.      | Coefft.  |
|  Period      |    On       |  Off       |   (kW)
|   (kW)       |             |___________|__________|__________|
|-------------|------------|------------|----------
---|---------------|  | Heating   |  0.000  |  0.248  |
|      1       |           |             |
|              |  | Cooling    |  0.000  |  0.519  |
|      2       |           |             |
|              |  | Lights     |  0.480  |  0.490  |
|      3       |           |             |
|              |  | Occupants  |  0.200  |  0.227  |
|      4       |           |             |
|              |  | Equipment  |  0.100  |  0.372  |
                                                     | Radiant

|Occupation|Occupation|Infiltr.  |Ventil.   |Lighting
|Occupancy |Occupancy |Equipment |Equipment |
|Period    |Duration  |Air       |Air       |Gain
|Sensible  |Latent    |Sensible  |Latent    |
|          |          |          |          |
|Gain      |Gain      |Gain      |Gain      |
|          | (hrs)    | (ach)    | (ach)    | (W/m2)   |
(W/m2)    | (W/m2)   | (W/m2 )  | (W/m2 )  |
|----------|----------|----------|----------|----------|-
----------|----------|----------|----------|
|    1     |    10    |   2.000  |   0.000  |   3.000  |
3.500      | 0.000    | 0.000    | 0.000    |
|    2     |     5    |   0.500  |   0.000  |   0.000  |
0.000      | 0.000    | 0.000    | 0.000    |
|    3     |     9    |   2.000  |   0.000  |   3.000  |
3.500      | 0.000    | 0.000    | 0.000    |
```

Table 3:Construction database for the composite insulation of the Test Room and its thermal property (program output)

```
| Program      A-Tas 8.31

| C-Code:   ceiling/5        | Construction name:
ceiling                                           |

 OPAQUE CONSTRUCTION

| External      | Internal      | External     | Internal     |
Conductance |  | Time         |
| Solar         | Solar         | Emissivity   | Emissivity   |
|   | constant  |
| Absorptance | Absorptance |                |              |
(W/m2 C)      |  | (hours)     |

|   0.600       |   0.400       |   0.900      |   0.900      |
1.148   |       |   5.2         |

|Layer | M-Code             | Width      |. Conductivity|
Density | Specific Heat    | Convection | Vapour     |
|Number| &                  |            |            |
|              | Coefficient | Diffusion |
|      | Material Name      |  (mm)      |  (W/m C )  |
(kg/m3) |  (J/kg C)         | (W/m2 C)   | Factor     |
|------|------------------|----------|------------|----
------|----------------|----------|------------|
|Inside| amlplast/11        |   12.70  |   0.420    |
1200.0 |  837.0             |    -       |   11.000   |
|      |   PLASTER 1 *4
|  2   | amlconcl/1         |  127.00  |   1.400    |
2360.0 | 1030.0             |    -       |   34.000   |
|      |   CONCRETE 1:2:4 *3
|  3   | amlplast/11        |   12.70  |   0.420    |
1200.0 |  837.0             |    -       |   11.000   |
|      |   PLASTER 1 *4
|  4   | amlcav/26          |  500.00  |    -       |
-  |    -                | 0.050      |   1.000    |
|      |   500MM AIR (DOWNWARD FLOW)
|  5   | amlins/18          |    1.50  |   0.045    |
70.0  | 1000.0             |    -       |   40.000   |
|      |   PVC, EXPANDED *2
|  6   | amlins/14          |   12.70  |   0.033    |
25.0  | 1200.0             |    -       |  192.000   |
|      |   POLYSTRENE, EXPANDED, CLOSED CELL *3
|  7   | amlins/18          |    3.00  |   0.045    |
70.0  | 1000.0             |    -       |   40.000   |
|      |   PVC, EXPANDED *2

   U VALUES (W/m2K):            0.959  (Wall)       0.983
(Roof)       0.905  (Internal)      0.987  (Ground Floor)
```