A study of a passive cooling technique: possibilities of using operable roof insulation in the warm humid tropics

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ABSTRACT: The impact of solar radiation on the roof is significantly higher than any other building element particularly in the Tropics. In Dhaka, a city in the humid tropics, almost all of the buildings have flat concrete roof and often without proper insulation. Giving way to elevated indoor temperatures usually above local comfort level in a context where active means of cooling is very expensive. This paper presents the results of an experimental study supported by dynamic simulation of the thermal performance of operable roof insulation over a typical flat concrete roof. A full scale field study was conducted in a test room to evaluate the radiant cooling potential of employing this technique with a view to establish a causal relationship between the operability of insulation and comfort. Contrary to established notions regarding limitations of radiant cooling in humid conditions, promising results indicate potentials for cooling by long wave radiation in the said climatic context. In conclusion the findings provide the basis for the development of design guidelines for the given climatic context.

Conference Topic: 0-energy built environments
Key words: Passive cooling, Operable roof insulation, Thermal comfort.

1 INTRODUCTION

Dhaka with its pattern of urban situations distributed over a combination of natural and man-made landscape provides opportunities to study the complex and dynamic processes of urban microclimates; but their effects are largely controlled by local events. Therefore it is not possible by regional climatic studies to register such transient phenomena. A study at a local scale has the potential for a broader understanding of the nature and the mechanisms of the climatic process-taking place in such conditions.

As this study deals with the thermal performance of operable roof insulation with special reference to Dhaka, a field study was essential to evaluate this phenomenon with a view of to establish a causal relationship between roof insulation and comfort. Because if a roof of high thermal mass is exposed to the sky during the night, it is cooled down by long-wave radiation, and frequently as well by convection to the cooler outdoor night air, making the roof mass into cold energy storage.

The following sections present the results of a fieldwork on thermal performance of operable roof insulation carried out in a Test Room located at Dhaka as a part of this work.

2 METHODOLOGY

The fieldwork was conducted in a test room located on a top floor of a four-storied building in Dhaka. Environmental data were collected with the help of Data Loggers and sensors for couple of days for the test room. Prior to data collection for insulated roof a Pre-Run period continued for seven days to reduce thermal inertia of the roof. With operable insulation system data were collected at 450 mm above the roof, which is the minimum height of parapet generally used in Dhaka

Period of observation was in the months of April, and June (2002) representing Pre-Monsoon and Monsoon period and the general climate during these periods are hot-dry and hot-wet respectively [1] [2] [3] The former is characterized by low humidity and low cloud cover, high temperature, high radiation, while the later is characterized by heavy rainfall, high humidity and temperature These two periods are most persistent and dominant; at the same time most extreme climatic values are registered during these period. Hence addressing environmental issues of these periods in terms of studying thermal performance of operable roof insulation can be of considerable importance. Observations on environmental factors made during the fieldwork are categorized into two groups,

- Some factors relate directly to thermal behavior such as ‘Indoor Air Temperature’, ‘Globe Temperature’ and ‘Ceiling Temperature’. These factors are directly influenced by roof insulation
- Some factors relate to thermal impact, such as ‘Roof Top Temperature’. Roof insulation is influenced by this factor.
2.1 Instrumentation

Data loggers were installed in the test room for collection of various climatic data. The remote data loggers recorded indoor air temperature and relative humidity with the help of built-in sensors, while outdoor air temperature, globe temperature, ceiling temperature and roof top temperatures were recorded with the help of external sensors. Data were recorded at intervals of one hour.

The sensitivity of and the manufacturers calibration of the data loggers were compared with the metrological recording (under similar conditions) in Agargaon Meteorological Office, Dhaka, Bangladesh and was found to be satisfactory.

2.2 Installation of Data Loggers

The data loggers were installed in the test room at two points at a height of 1.62 meter (which is average minimum man height in Dhaka’s local context) from the floor level of the test room (Fig. 1). Loggers were mounted on the wall with the help of hook and loop tape A black colored table tennis ball (matte finish) housing a sensor inside and suspended from the wall by means of a support to measure globe temperature [4] [5]. External sensors were shielded from direct radiation and from rain. Sensor collecting ceiling temperature was insulated from outside to avoid radiation gain.

2.3 Construction and Installation of Operable Roof Insulation

Certain criteria were followed for selection of insulation material:

- Materials, which will be selected for insulation, should have low thermal conductivity, preferably between 0.03 W/m deg C for insulating materials and up to 400 W/m deg C for metals. [6].
- Color should be light, preferably white and should have reflective quality to reduce solar radiation penetration [7] [8].
- Materials should be capable of resisting weathering effect and lightweight.

- Materials should be easily available in the market and inexpensive.

Considering all above circumstances a composition of three materials were chosen to fabricate operable insulation. Main insulating material is 12.7 mm thick Styrofoam panels sandwiched between PVC sheets. Styrofoam is low conductive material, widely available and inexpensive, but can’t withstand weathering effect. Therefore white colored reflective PVC sheet is used for protection, additional insulation and making the panels operable. The Transmittance value (U value) of this composite membrane is 0.646 W/m² deg C.

PVC sheet used at the top cover of Styrofoam is 3mm thick; white colored and reinforced by threads at the back, while the bottom cover is 1.5 mm thick PVC sheet. These two sheets are sewn together on three sides to form an envelope to a length similar to the length of the test room. The combined sheet is again sewn transversely at the interval of 355 mm to form a series of pockets. Styrofoam panels, which are available at 305 mm width, are inserted within the pocket to form the complete insulation. The working principle is illustrated in Fig.2.

2.4 Description of the Test Room

The primary criterion for selecting the test room was that, it should be either single storied building or should be located at the top floor of a multistoried building in Dhaka and the roof should

Figure 1: Working Principle of operable roof insulation

Figure 2: Positions of Data Loggers and External Sensors in the Test Room

\[ U=1/R_a \]

\[ \text{External surface resistance } 1/f_e = 0.15 \text{ m}^2 \text{ deg C/W (heat flow downward)} \]

PVC (Top layer) \[ b/k = 0.003/0.16 \quad 0.01875 \text{ m}^2 \text{ deg C/W} \]

Styrofoam \[ b/k = 0.027/0.01 \quad 1.27 \text{ m}^2 \text{ deg C/W} \]

PVC (Bottom layer) \[ b/k = 0.0015/0.16 \quad 0.0093 \text{ m}^2 \text{ deg C/W} \]

Internal surface resistance \[ 1/f_i = 0.1 \text{ m}^2 \text{ deg C/W (still air condition)} \]

Total resistance \[ R_t = 1.646 \text{ m}^2 \text{ deg C/W} \]

\[ U=1/R_t \]

\[ = 0.646 \text{ W/m}^2 \text{ deg C} \]
Dhaka Monsoon is the most prolonged season characterized by high values of humidity, represents the Monsoon or hot-wet period and serves as a base case to evaluate the performance of roof insulation. The intent of this investigation is to study the thermal performance of operable roof insulation. Therefore, uninsulated roof has been considered as a base case to which operable insulation on roof at different heights can be compared. The south side of the test room are constructed with .254 m brick wall, plastered and light-cream colored plastic paint on interior walls. White cast in situ mosaic on the floor. There were four incandescent lights each with 40 watt (occasionally used), one fluorescent light 40 watt (regularly used) and a ceiling fan in the test room.

3 FIELD INVESTIGATION

Major findings of environmental condition of the Test room are discussed in this section and it is divided into the following (1) Field results: Test Room without Operable Roof Insulation (2) Field Results: Test Room with Operable Roof Insulation. The intent of this investigation is to study the thermal performance of operable roof insulation. Therefore, uninsulated roof has been considered as a base case to which operable insulation on roof at different height can be compared. In the evaluation process certain environmental criteria, which are directly influenced by roof insulation like Indoor Temperature, Globe Temperature and Ceiling Temperature in the test room have been considered. Rooftop temperature has also been taken into account as roof insulation can play an important role. The significant findings of environmental variables considered for the evaluation of thermal performance of operable roof insulation.

3.1 Field Result: Test Room without Operable Roof Insulation

Field study was carried out in June as a base case to evaluate the performance of roof insulation. This month is selected because it represents the Monsoon or hot-wet period and characterized by high values of humidity, temperature, cloud cover and radiation. But the clearness index is low. Moreover in the context of Dhaka Monsoon is the most prolonged season.

a) Indoor Air Temperature

Indoor temperature of a room depends on certain external factors, where roof insulation can play an important role. The significant findings of temperature data recorded from field investigation for the test room without roof insulation case are described below:

The average indoor air temperature was 31.38 °C recorded during the period of field data collection which is almost near to the upper limit of the comfort range in still air situation. However, during the field survey was recorded as 31.57 °C, which is near to the upper limit of summer comfort zone in still air situation. The Globe maximum temperature was recorded as 34.43 °C (over the comfort range) and the minimum as 29.1 °C, creating a difference of 5.33 °K. The diurnal difference of maximum and minimum GT was recorded between 2.05 °K to 4.07 °K and the time lag between them varies by 6 to 9 hours.

The representative day (Fig. 4) illustrates that Globe Temperature ranges between 30.04 °C to 33.45 °C. It should be noted that for the majority of the hours average Ceiling and Rooftop temperature was over GT. As there was no insulation on the roof there was no obstruction to the passage of incoming heat through the roof. As a result, warm condition prevailed in the test room.

b) Globe Temperature (GT)

Globe Temperature is an average temperature of the surrounding surfaces. It includes the effect of incident solar radiation and has as great an impact as air temperature. The average GT during the field survey was recorded as 31.57 °C, which is near to the upper limit of summer comfort zone in still air situation. The Globe maximum temperature was registered as 34.43 °C (over the comfort range) and the minimum as 29.1 °C, creating a difference of 5.33 °K. The diurnal difference of maximum and minimum GT was recorded between 2.05 °K to 4.07 °K and the time lag between them varies by 6 to 9 hours.

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c) Ceiling Temperature

As ceiling is closely related with the roof and also due to its physical positioning, any temperature fluctuation on roof directly affects the ceiling temperature. A warm ceiling increases indoor temperature of the room below by convection and radiation process, therefore it is a significant factor to be considered. According to the logged data the maximum ceiling temperature during the field investigation was recorded as 42.46 °C. The situation will be worse if airflow is introduced to achieve thermal comfort. The minimum ceiling temperature and Relative Humidity profile of the Test Room without insulation (18-20 June, 2002)
The representative day summary of environmental variables (Fig. 6) illustrates that GT ranges between 28.44 °C to 31.8 °C within comfortable range (Mallick, 1994). Lower temperature regime was observed in the morning hours while the higher regime during evening hours.
It should be noted that average Globe, Ceiling and Rooftop temperature followed a similar pattern during study period with maximum deviation of 2.09 °K. Above circumstances indicates that roof insulation has influence on GT as it obstructs the major passage of incoming heat through roof and help reduce radiant temperature leading to a comfortable environment.

Figure 5: Temperature and Relative Humidity profile of the Test Room with Operable Roof Insulation at 450 mm above the roof (23-25 April, 2002)

Figure 6: Average value of Temperature and Relative Humidity of the Test Room with Operable Roof Insulation at 450 mm above the roof (23-25 April, 2002)

4 COMPARATIVE STUDY

Foregoing sections describe the thermal environment in the test room with respect to uninsulated and insulated (operable) roof. A comparative study is made to judge the thermal performance of operable roof insulation with respect to thermal comfort. The performance evaluation is made on the basis of, Temperature Difference, Comfort Zone analysis. Details are discussed below:

a) Temperature Difference (Roof Top Maximum vs. Ceiling Maximum)

According to the field results for uninsulated and insulated roof, considerable amount of temperature disparity between maximum rooftop temperature and maximum ceiling temperature is evident in the test room when the roof is uninsulated. This temperature difference contributes to elevate ambient temperature of the test room and cause discomfort. But when the roof is covered with operable insulation, a different situation is observed. On the first day heat storage is reduced to 1.61 °K while in uninsulated condition it is 5.54 °K during second and third day of data collection roof temperature has gone below the roof temperature when the insulation is placed at 450 mm above the roof (Fig. 7). The cooled mass of the roof then serves as a heat sink and absorbs through ceiling the heat penetrating into and generated inside the buildings interior during daytime hours. Again when the roof is exposed to night sky it loses heat by long-wave radiation and convection that reduces thermal storage capacity of the roof, therefore ceiling collects heat from the surroundings and may attain higher temperature than roof. Thus, the concrete roofs, which are very common in Dhaka, with applied
Figure 7: Temperature difference (Roof Maximum-Ceiling Maximum) in Test room for Uninsulated and Insulated roof.

Operable insulation, can provide effective radiant cooling and maintain the indoor temperature well below the outdoor level.

b) Temperature Difference (Globe Maximum vs. Indoor Maximum)

Another way of assessing thermal performance of operable roof insulation was done by measuring temperature difference between Globe Maximum and Indoor Maximum. As of all other environmental variables, globe temperature is the best indicator of comfort and may be the reason why people feel comfortable at low radiant temperature when air temperature readings are high. Temperature difference between daily Globe Maximum and Indoor Maximum clearly indicates that a higher temperature regime exists in the test room when the roof is uninsulated. Not only the magnitude of Globe and Indoor temperature is higher but their difference is also greater (Fig. 8) in uninsulated situation. On the other hand, when the roof of test room is covered by means of operable insulation, a lower temperature prevails as compared to previous one. Insulation reduces the process of heat transfer from roof to the interior, it increases Thermal Time Constant (TTC) [10] of the material; therefore radiant gain becomes slower and accelerates nocturnal cooling process. Therefore in insulated instances we observe almost similar temperature trend between globe and indoor maximum temperature profile and they are within the summer comfort zone in still air condition, while the temperature exceeds the comfort zone in uninsulated situation.

c) Comfort Zone Analysis

Comfort zone is outlined on the basis of indoor air temperature, relative humidity and air flow, particularly devised for summer comfort. In still air situation, 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.

Fig. 9 is a scatter diagram showing the relationship between Relative Humidity and Indoor Temperature of the test room with uninsulated roof. After superimposing summer comfort zone on the figure, certain thermal information can be traced out. Half of the points are outside the comfort zone (still air situation) and majority of points are concentrated between 70%-85% RH and 30-34 °C. Some of the points are found towards higher relative humidity zone and below 30 °C temperatures. However with the increase of air flow comfortable condition can be achieved. The diagram for comfort zone analysis for the test room with operable roof insulation at 450 mm (Fig. 10) illustrates that, instead of concentrated points they scatter within the comfort zone.

Figure 8: Temperature difference (Roof Maximum-Ceiling Maximum) in Test room for Uninsulated and Insulated roof.

Figure 9: Indoor Temperature and RH plots of Test Room with Uninsulated Roof on Summer Comfort Chart

A concentration can be traced between 65-70% relative humidity and 30-32 °C. Very few points are located just outside of the higher level of comfort zone. A much better environmental condition exists here as compared to uninsulated condition.

Figure 10: Indoor Temperature and RH plots of Test Room with Insulated Roof (450 mm) on Summer Comfort Chart
5 CONCLUSION

The above-mentioned findings establish that test room with operable insulation attains more comfortable situation. Obviously the indoor environment is better in comparison to uninsulated situation. Insulation not only cuts down the effect of sol-air-temperature on the roof, which is the main source of heat gain in Dhaka and keep Globe temperature within comfortable range but it also facilitates nocturnal cooling potential. Situations like Dhaka where majority of the period in monsoon and post monsoon period sky is overcast with cloud; even in these circumstances principle of operable insulation works. So this system of roof insulation can be applied to single storied buildings and top floor of multistoried buildings as it has the promise in generating comfortable thermal environment.

6 REFERENCES


