Design and Validation of Solar Calorimeter

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Abstract

One of the more efficient and cost effective passive methods for reducing the cooling (heating) load of a building is with the use of solar insulating materials. CSEM-UAE has performed a theoretical study of different cost-effective and thermally efficient solutions regarding the solar insulating materials for buildings. The preliminary laboratory scale calorimetric study on solar insulating materials showed that energy savings of 20-30% can be obtained with different solar insulating and reflective materials. To perform a real outdoor test of the savings obtained with solar insulating materials, a solar calorimetric test facility has been designed. The present design is aimed at determining the energy savings of different measures with similar indoor conditions, with and without solar insulating materials for the same ambient conditions. The design and simulation results of the test facility with various solar insulating materials are presented in this paper.

1. Introduction

In order to reduce energy use throughout the world, a focus needs to be made on energy improvements in new and existing buildings. Buildings are one of the largest energy consumption segments and also one of the largest contributors to the increase in an atmospheric CO_2 resulting in global warming and climate change, making them a great place to start reducing energy usage. The total energy consumption of buildings, both residential and commercial, has steadily increased reaching figures between 20% and 40% of global energy in developed countries [7]. HVAC account for approximately 70% of the total building energy consumption. This is especially true in the Middle East. In Saudi Arabia it is estimated that two-thirds of the electric energy is used in buildings and two-thirds of that energy is used for air conditioning (AC) units to compensate for heat transmission through the building envelope [3]. The average total energy consumption of residential households in the United Arab Emirates is around 40% of all energy consumed, according to the International Energy Agency [4].

In most projects in the UAE, building materials are evaluated and selected based on aesthetics and cost and not on their energy and environmental performance. It is, therefore, not surprising electricity use for cooling in building sector is in the range of 50% to 73% of the total consumption with an average of 60% [2]. The growth in electricity consumption for cooling buildings in the UAE region has increased ten times (from 5 to 50 Billion kWh) over the past two decades. The net energy consumption of the UAE reached 52.6 Billion kWh [6] and UAE has the highest ecological footprint in the world with total annual CO_2 emissions of 137.8 million metric tons [2]. Therefore, energy efficiency in buildings is today a prime objective for energy policy. Reducing the cooling load in these areas is one of the most effective energy conservation measures in buildings that can potentially be achieved with a combination of building design, thermal insulation, and reflective coatings.. However, there are many variables that affect a building's energy use such as; climate, building orientation, building construction materials, mechanical equipment, lighting, people, activity, etc. With the proper materials and installation techniques, a building façade can slow or even reflect heat gains away from the indoor space. The present study is aimed at designing a solar calorimetric test facility that measures the energy savings of an air conditioner (by reducing cooling load) using various methods with solar insulating materials in real conditions. The design of solar calorimeter and simulation results is discussed in coming sections.

2. Design of Solar Calorimeter

While energy savings are encouraged for all building types, there is a critical point in which the marginal cost of adding more insulating materials will match the marginal cost of cooling the indoor air. Proper building modeling and simulations must be performed alongside economic energy analyses, in order to determine the optimum design for any particular construction project. There are many software packages today that can describe the heat load calculations necessary to model a building's thermal characteristics. Though very complex, these software programs lack the ability for rapid modeling of buildings to determine a relative heat gain profile. In this work, CSEM-UAE developed an excel model that can accurately determine the heat loads of several simple buildings models and determine the optimal design configuration. From this model, a solar calorimetric test facility was designed to test energy savings of current and new insulating materials in the test facility based on the amount and properties of each solar insulating material. This model was also used to quantify and predict the heat flux properties of aging and weathered building materials. In addition, these designs for a test facility in real climatic conditions are utilized to verify the simulation model for accuracy, and to test new materials for their thermodynamic characteristics.

This model is aimed to identify a procedure for quickly and easily modeling a wide range of simple building configurations and to comparatively analyze them. Two buildings can be tested under exactly the same conditions. The first one acting as a reference with commonly used building materials in the UAE and the other with an added insulating energy saving measure. By comparing both of the test results and subtracting out the contributions from the reference, what is left is the effect that a solar insulating material has on the energy consumption and heat profile of a building and the energy savings potential can then be determined.

One interesting feature of this design is the moveable insulation panel. The idea behind this adjustable insulation was that there were two opposing interests taking place. First, the heat gain through the façade should be concentrated into the smallest possible area, while all other surfaces are kept insulating. This is similar to how a calorimeter is designed. Second, there is a need for testing to be performed both on the roof and vertical wall surfaces, to account for things like windows, coatings, and dust accumulation that could not be done on either surface alone. The only solution seemed to be to moderately insulate both the south and roof surfaces (the two main insolated surfaces) and test a new material on both surfaces. A novel solution was to include a moveable piece of insulation and switch its location depending on the season or testing surface. During the winter, when the sun is low in the sky, tests should be done on the south wall and the moveable insulation will be placed on the roof of the test building. During the summer, this insulation is moved to the south wall, so that the roof, which is now absorbing a great deal of the high angle insolation now becomes the test surface. This solves both problems: it reduces the testing surface area or increases the percentage of heat gain through the test surface, and also allows for testing to be performed on both vertical and horizontal surfaces.

There are many factors that contributed to the design choices that have been implemented for the solar calorimeters. By examining the goals and limitations set up for this facility, several different choices had to be made about size, shape, thermal properties, layout, and testing scope. One of the most important choices was the makeup of the building components. In order to test the relative energy savings between a reference calorimeter and an added energy saving measure to a building, they both must be identical as much as possible, except for the added insulation or coating that is to be tested. In this manner, it is possible to isolate the effects of this new measure with regard to its thermal and radiative properties. Before testing takes place, all buildings will be calibrated with one another to ensure consistency. During testing, all buildings will have an air conditioner (AC) to maintain constant indoor temperature. With this in mind, the heat gained by the least insulated building must be able to be removed by the air conditioning unit to maintain thermal comfort. The limit of the maximum hourly heat gain excluding internal heat load was chosen to be in the range of 3 $kW_{thermal}$, which corresponds to approximately 1 ton of cooling capacity potential from the AC unit. Also, the building must be able to include space for the measurement devices or data collection, fasteners and wiring fixtures for the AC unit. By adjusting the amount of thermal insulation and the size of the buildings, it was possible to determine which sets of sizes and materials would fall within an acceptable range to be considered.

During the design process, consideration was taken into account regarding the shape of the building. A comparison between a square building and one with a slanted roof was considered. Simulations were performed to compare two equal volume prototypes made of the same materials one with a flat roof and another with a slanted roof to the optimum yearly inclination angle (approximately the local latitude angle). It was observed that both configurations result in approximately the same heat loads throughout the year. The difference is a result of the slight variation in the roof area and the solar incident angle influence on the slanted roofs heat load during the winter months (~10% difference overall). It was decided that the roof should be flat instead of slanted because of several reasons: the heat flux would not be greatly affected, it would be much easier to construct and is the more common roof type for the area. A constraint that was imposed on all the test facility was to set the height of each building to 3 meters. It was decided to keep this height for a couple of reasons; first in order to reduce shading from one building to another there must be some separation distance between them. A shorter building would require less shading separation in this case. Secondly, it would be more difficult to access the roof of a taller building when they require the addition of a coating or insulation.

The simulation model is capable of cycling through all possible configurations for the length, width, and height of a building over a given range and returns the resulting maximum heat load value over the year. In this way, it was possible to show which dimensions came close to a maximum 3 kW_{th} heat load. While some configurations were 3m long, there were also other configurations that were 4m and 5m long as well. The materials that would constitute the test facility were chosen based on the thermal and physical properties of a material. Before any particular material was chosen, a simulation was performed by changing the total average R-value for all surfaces along with changing the dimensions of the calorimeter for all configurations within the criteria. These results are given in Fig.1 and this helped narrow down the number of possible configurations that fell within the criteria. From Fig.1, several designs were chosen around the 3 kW_{th} maximum heat load range for different R-values and sizes, represented by the dashed oval. The best configuration was chosen based on the small overall size, low average R-value and the wall dimensions.

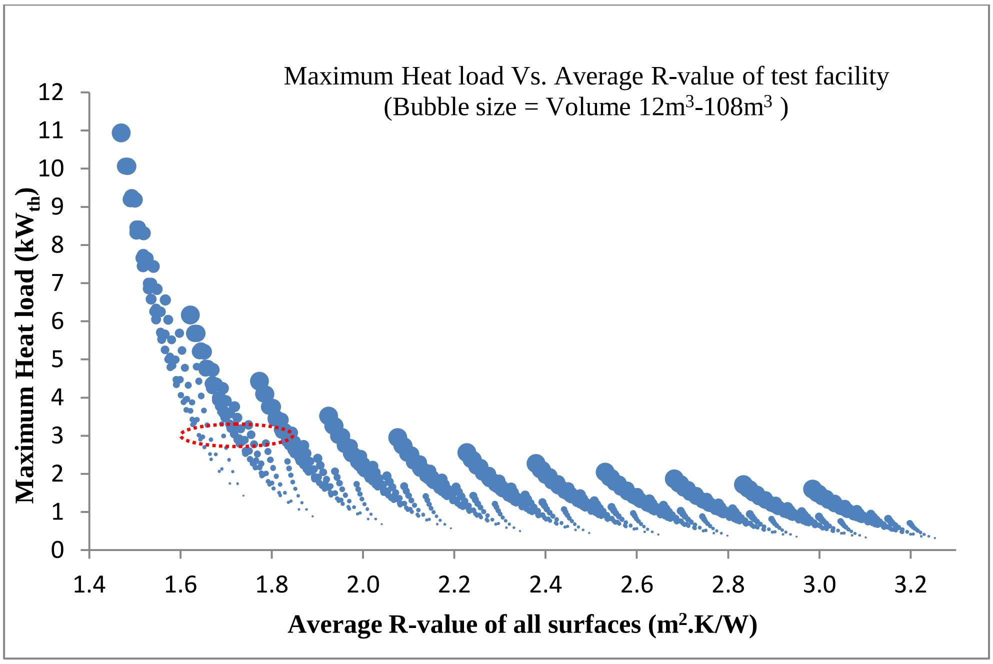

Figure 1– Maximum building heat load for different R-values and sizes (2mX2mX3m to 6mX6mX3m)

The dimensions of the building were chosen to be 3 x 3 x 3 meters for easy access to the roof, reduce the shadow length and that a smaller footprint is needed for the analysis. This design meets several of the criteria, such as small size, a 3kWth maximum heat gain, testing flexibility, local materials, and reproducibility by the software model. Four cubicles facing true solar south were built at CSEM-UAE outdoor laboratory as shown in Fig. 2. In the four buildings, the first is the reference, second for testing coatings, third for testing insulation materials and the last one has no south wall in order to test innovative construction materials and techniques. The energy savings of added insulation or coating on any building is always compared to the reference.

Figure 2- Layout of outdoor test facility

The test facility can evaluate the performance of existing solar insulating materials for new buildings or to retrofit existing ones and for the development and comparative evaluation of new green building material and construction techniques. This facility is open to industrial cooperation and to academic research and development projects. It is highly beneficial for customers in performance evaluation of solar insulating materials in UAE climatic conditions. They can also benefit from the existing facility to develop new or modify existing insulating materials to earn market shares in the Middle East region.

3. Results and Discussion

Using the test facility design described above, a series of simulations were performed to determine the effects of adding solar insulating materials to the testing surface of the solar calorimeter, on the total cooling load and relative energy savings. During summer (March 1st to October 1st) the test surface is the roof, and the rest of the year the test surface is the south wall. The addition of insulation on the test surfaces was performed for several simulations and in general the heat flux through the test wall decreased with an increasing R-value. Fig. 3 shows the maximum heat load, average daily heat load, average thermal energy savings and total thermal energy saved are relative to the original R-value of the testing surface. Results are shown based on adding thermal protection in relation to the original amount of insulation because there is a reducing marginal benefit for every unit of added thermal protection. For example, adding 5cm of polystyrene (≈0.15 W/m.K) to a concrete wall (≈0.18 W/m.K) will save much more energy per unit insulation that adding it to a moderately insulated wall (≈2.1 W/m.K).

Simulations were performed by varying the absorptivity of the testing surface and the results are shown in Fig.4. The savings that result from the addition of a reflective coating to a surface are due to the insolation that is reflected away from the building envelope. The results shows that 23% daytime savings and 19% overall energy savings can be obtained by reducing absorptivity from 0.6 (reference) to 0.4(test surface).

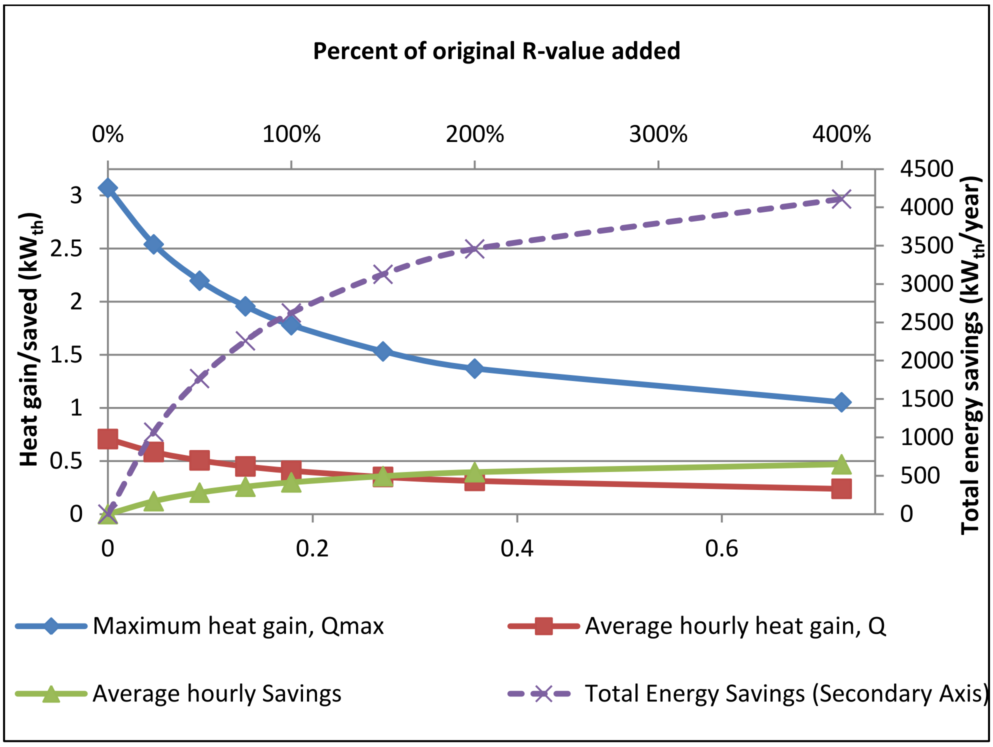

Figure 3 Results of added insulation on heat gains and energy savings

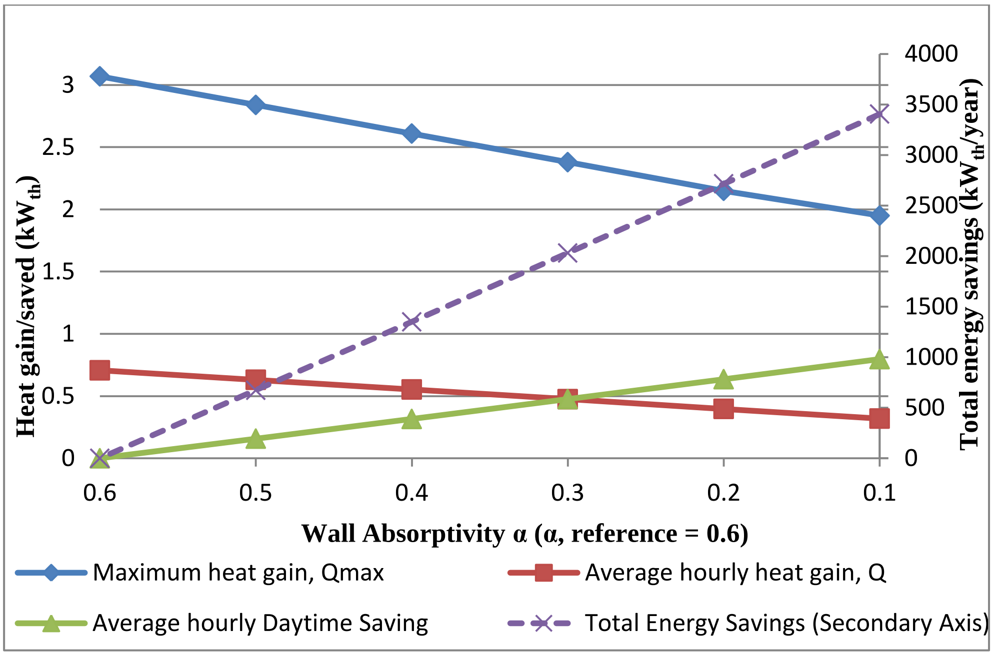

Figure 4 -Results of lowered surface absorptivity on heat gains and energy savings

These savings are directly proportional to the amount of incident radiation, assuming the source is spectrally distributed similarly to a black body source (i.e. the sun). Unless the coating layer is thick enough or has a very low thermal conductivity, there will be no savings during the night where thermal conduction dominates the heat transfer. In the case of reflecting coatings, it is more important to place the coating on the surfaces that receive the most amount of insolation, there by maximizing the savings effect of the coating. For example, in the northern hemisphere the southern facing surfaces and roof are the most insolated surfaces and would benefit the most from a reduced absorptive value. There is a linear relationship between the decrease in a surface’s absorptivity and a decrease in both maximum heat gain and average hourly heat gain. As well as a linear increase in both average hourly daytime savings and total energy savings over the year. It is worth noting that these averages are determined only during the daytime since the savings are derived from the reduced absorption of solar irradiation.

4. Validation

In order to verify that the simulation model was accurately calculating the heat gains through the designed test facility a comparison was simulated using TRNSYS building software. To ensure both software programs will be comparable, identical set of input parameters are chosen. With TRNSYS, there was no possibility to change the R-value of a surface over the year once the simulation is started so as a result the CSEM-UAE model is modified so that the roof is the only testing surface throughout the year with all other surfaces highly insulated. The deviation in cooling demand with both programs is shown in Fig. 5. The horizontal axes represent the day and time throughout the year, while the vertical axis is the relative difference between the two simulation models. Much of the deviation occurs during sunrise and sunset. TRNSYS predicts that the heat gain will be greater in the morning and less at night, compared to our model. This may be caused by the more complex algorithms that TRNSYS uses to calculate heat gains due to shallow angle insolation. Overall, the average error between the CSEM-UAE simulation model and TRNSYS model is -0.029 kW_{th} with a standard deviation of 0.044 kW_{th}. This error is small

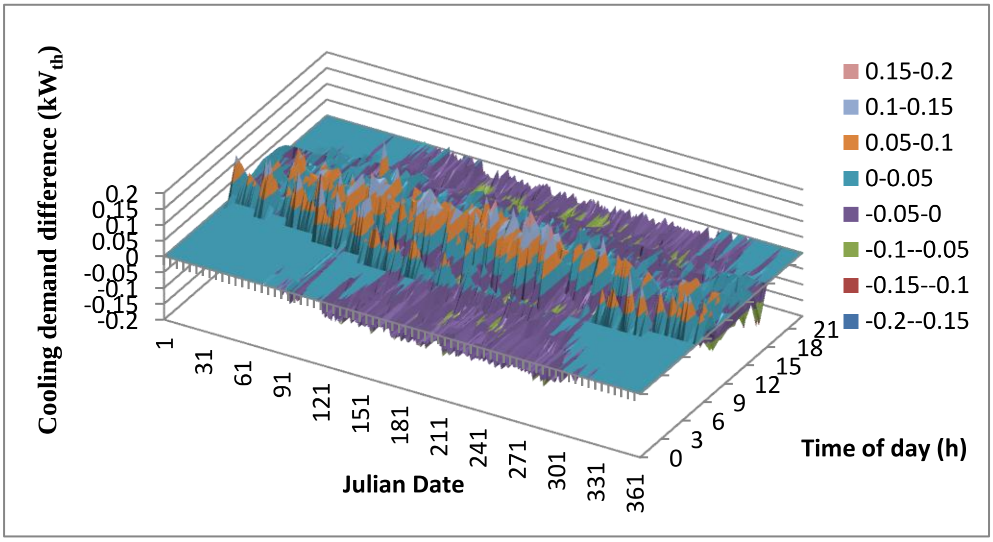

Figure 5 - Deviation in cooling demand of a building simulated with TRNSYS and CSEM-UAE simulation model for constant input parameters

compared to the amount of heat flux and these results confirm that the CSEM-UAE excel model should perform well in predicting heat gain in the proposed test facility. Also, systematic errors during the calibration of the multiple test buildings should be detected and fixed easily with the help from the software models.

5. Conclusions

The following conclusions have been made from the present work:

- Simulation model in excel has been developed to design test facility.
- Test facility design was optimized by concentrating heat gain through the façade into the smallest footprint, while all other surfaces are kept insulating, similar to how a calorimeter is designed.
- Four buildings have been developed to evaluate the performance of different solar insulating materials in real conditions against a standard reference building.
- Simulation studies shows that an energy savings of up to 20% can be achieved by adding R-1.5 (5cm) of polystyrene to the testing surface compared to reference.
- Reflective coatings have considerable effect on daytime energy savings in buildings.

Simulation results will be compared with the ongoing experimental studies in real conditions.

6. Acknowledgement

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7. Reference

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