

The Effect of Heat Gain on the Performance of a Radiant Cooling System

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Abstract

A test cell that simulates a closed building with shaded windows is used to analyse the effects of the heat gain on the performance of a radiant cooling system. The cell has a light metal double-sloped roof at the outside, which acts as a nocturnal radiator and below this roof are hinged, lightweight and operable, reflecting panels that are closed during the day and open at night. The performance of the system is evaluated with different conductive heat gain coefficients and its performance can be defined as a function of the U_a value, which also affects the swing and temperature distribution. A lower U_a generates a higher temperature swing inside the cell and higher temperature differences between the upper and lower regions of the cell. Equations and figures that predict the performance of the cell as a function of the heat loss coefficient and the insulation levels of the wall are presented while in another paper other equations that predict the indoor maximum temperature as a function of the outdoor average temperature, the swing and the U_a value are presented.

Conference topic: Methods and tools for design-assistance

Keywords: radiant cooling, passive cooling, affordable housing, bioclimatic architecture

INTRODUCTION

Metal roofs are common in many developing countries. These roofs are very hot during the daytime but cool down quickly in the evening, when they lose the heat to the night sky by convection and radiation. If the sky is clear then the temperature of the metal roof will be lower than the air and heat will be removed through the roof to the upper atmosphere. Temperature inside small homes built with these roofs are dominated by the performance of the roof, so that temperatures during the day can be many degrees higher than outdoor air temperature.

Installing un-flammable, operable hinged interior insulation plates under the roof can greatly reduce daytime heating without interfering too much with the cooling effect of such roofs during the nights. The effectiveness of storing the "cold energy" generated by the nocturnal radiant cooling for lowering the indoor air temperature during the daytime hours depends on the thermal storage of the interior space [1]; [2]. The distribution of the mass also affects the performance of the cooling system [3]; [4]. This research is testing the effects of the radiant cooling under specific conditions of the insulation and thermal mass. The effects of these factors is tested in successive series. Eventually, the cooling effect will be expressed as a function of the overall properties of the test cell (U_a of the envelope and mass), and the climatic conditions, so that it would be possible to estimate also the expected performance in buildings (assuming that the windows will be closed and shaded during the daytime).

THE RADIANT COOLING SYSTEM

A Radiant Cooling System was developed by Givoni [1] at UCLA in 1996. The system has a radiant barrier mounted on an operable hinged interior insulation plate. The plates are closed during the day, blocking radiation to the test cell, and open at night permitting the roof to absorb heat from the space and transfer it to the night sky, cooling it (Fig 1). The rotation of the insulating ceiling panels between the horizontal (closed) and vertical (open) positions is achieved by an electro mechanical system designed and built by A Gomez. Under computer control the panels are opened at sunset and closed at sunrise, according to a prescribed action schedule calculated for the longitude and latitude of Los Angeles. In a real home the panels can be controlled manually from the interior, e.g. by a rope. Interior operable insulation plates are not exposed to the wind and the rain and thus can be simpler in construction, lighter and much less expensive than external operable panels, making these systems suitable for installation in low cost housing of developing or developed countries.

EXPERIMENT

A series of experiments to determine the performance of the system with different combinations of insulation levels were performed at the University of California Los Angeles since the summer of 2001. The effects of combining the different insulation levels with mass placed in the horizontal or vertical position are also tested but will be discussed in another paper.

Test Cell

The test cell's internal dimensions are 1x1x0.95 m. and the walls and floor were 'super insulated' with polyurethane panels 8cm thick. There are 110 concrete bricks 89 mm by 57 mm by 190 mm and a weigh of 0.09 kg. each and which are used as thermal mass. The thermocouples are located at different points inside the test cell (Fig. 4). The two that are used in this paper are inside the main space of the cell at 660 mm and 300 mm above the wood floor level. Other measure the temperature of the metal roof, the mass of the bricks and the attic. The cell is not ventilated and does not have windows simulating a building with shaded windows which is closed during the daytime to avoid heat gains.

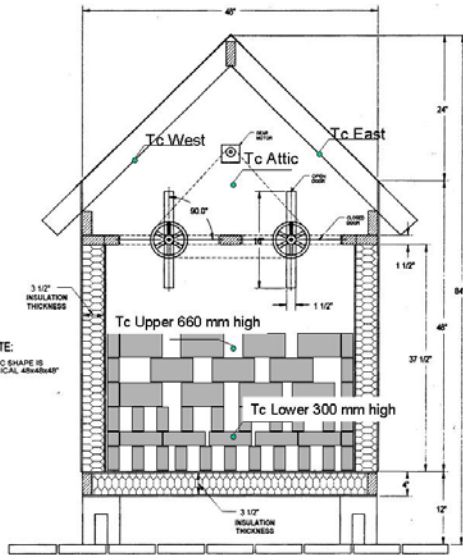


Figure 1: Section of the Cell with Mass.

Description of Series

The overall heat loss coefficient depends on the insulation level of the building envelope and the heat loss by infiltration or ventilation. The heat gain coefficient also takes into account radiant gains through windows. Since there are no windows in the test cell and the infiltration is assumed as equal in all the series, the variable to which the indoor temperature is related is the conductive heat loss (or gain) coefficient commonly called U_a . This value is calculated by multiplying the different surfaces of the test cell by their individual U values and adding the results. This number indicates potential heat gain/loss from the outdoors, in watts per degree difference, when the radiant system is closed.

Table 1. U_a of the different series

Series Number	Date	U value of Walls (W/m ² K)	Conductive Heat Loss Coefficient U_a (W/ K)
1	Oct 13- Nov 1, 2000	0.225	2.4
2	June 7-28, 2001	0.565	4.3
3	Dec 5 2001– Jan 10 2002	0.780	5.6
4	Nov 14- Dec 5, 2001	0.996	6.8
5	July 28 – Sept 7, 2001	1.21	8.1

The U_a value is altered by modifying the U value of the individual walls. The changes in the insulation level have been made in the following form: in series 1 all the walls are well insulated; in series 2 the insulation is reduced in the east wall; in series 3 the insulation is reduced in the east and north wall; in series 4 the insulation is reduced in the east, north and south wall; in series 5 the insulation is reduced in all the walls.

RESULTS

The reduction of the average and maximum temperatures inside the cell as compared to the outdoor values are a good indication of the performance of the system (table 2). These numbers, when coupled with the swing permits to determine a performance variable that compares the series.

Table 2. Maximum and average temperatures in the series

	Series 1	Series 2	Series 3	Series 4	Series 5
Avg. Max Lower	14.1	22.3	13.4	14.1	24.1
Avg. Max Upper	15.5	23.28	14.1	15.15	25.21
Avg. Max Outside	20.4	29.1	19.4	20.4	28.7
Avg. Lower	12.28	19.73	12.00	12.28	20.25
Avg. Upper	12.54	20.24	12.02	12.54	20.79
Avg. Outside	14.8	21.41	13.93	14.8	21.24

Series 1: $U_a=2.4$

The first series is with all walls with the highest insulation and was performed between October 13 and November 1 2000. Figure 2 shows a typical three day period during the series. Both the lower and upper thermocouple temperature follow the mass temperature closely and are very far from the outdoor maximum air temperature. The difference between lower and upper average maximums is only 0.6 K, while the difference between indoor lower maximum and outdoor average maximum is 7.9 K. The average temperatures at the lower and upper levels are similar and about 3 K less than the average outdoor temperature of 17.26 C.

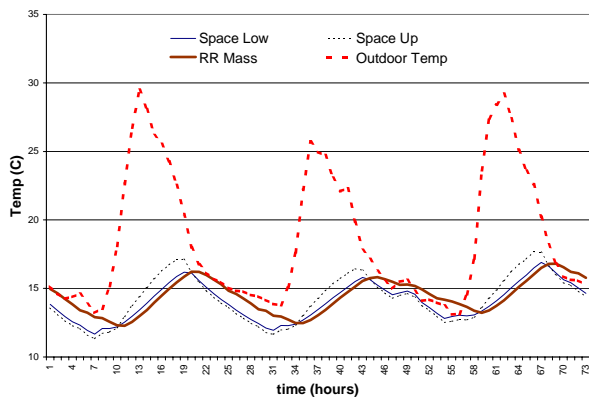


Figure 2: Three-day section of series 1.

Series 2: $U_a=4.3$

In this series, between June 7 and 28, 2001, the average insulation value of the walls is reduced to 0.565 W/ K m^2 , increasing U_a to 4.3 W/K . Figure 3 shows a three day period of the series. There is a difference of 1 C between the average maximum at the lower and upper heights. Indoor temperature is close to the mass temperature and the indoor average temperature at the lower thermocouple is 1.7 C less than the average outdoor temperature.

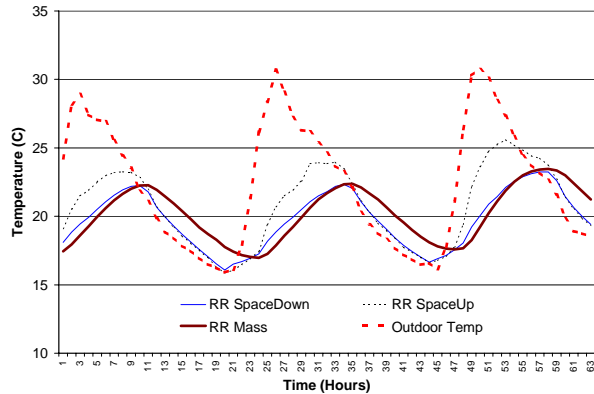


Figure 3: Three-day section of series 2.

Series 3: $U_a=5.3$

In this series, performed between June 7 and 28 of 2001, the average insulation value of the walls is reduced to 0.78 W/ K m^2 , increasing U_a to 5.3 W/K . There is no significant difference between the indoor averages and there is a difference of 1.93 C between the indoor average temperature at the lower level and the outdoor average temperature. The average temperatures inside are similar, but the maximums are not; there is a difference of 0.9 K between the indoor maximum averages at both levels.

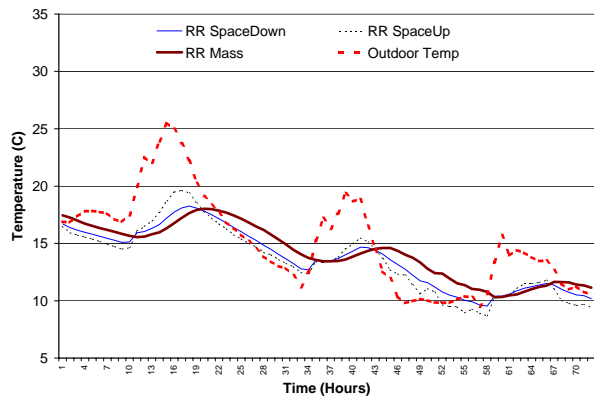


Figure 4: Three-day section of series 3

Series 4: $U_a=6.8$

In series 4, performed between November 14 and December 5 of 2001, the average insulation value of the walls is reduced to 0.996 W/K m^2 , increasing U_a to 12.96 W/K . There is a difference of 1.05 K between the indoor average maximums at the upper and lower levels. Indoor average values are close to each other at both levels and about 2 K lower than the outdoor average temperature of 14.8 C .

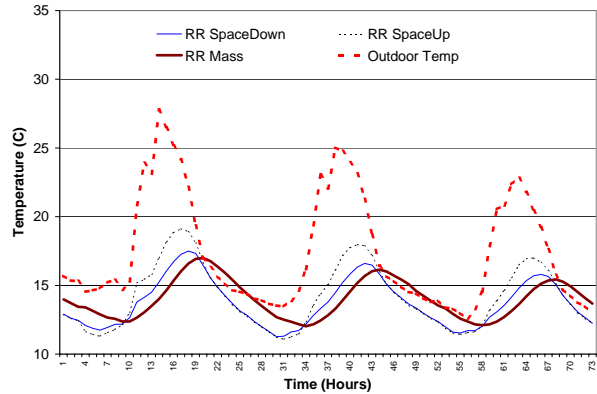


Figure 5: Three day section of series 4

Series 5: $U_a=8.1$

In this series, between July 28 and September 7 of 2001, the insulation value of the walls is reduced to its lowest level: 1.21 W/ K m^2 , increasing U_a to 8.1 W/K . The average indoor values as in all series are close together. The average outside is 1 K higher than inside at the lower level (Fig 6).

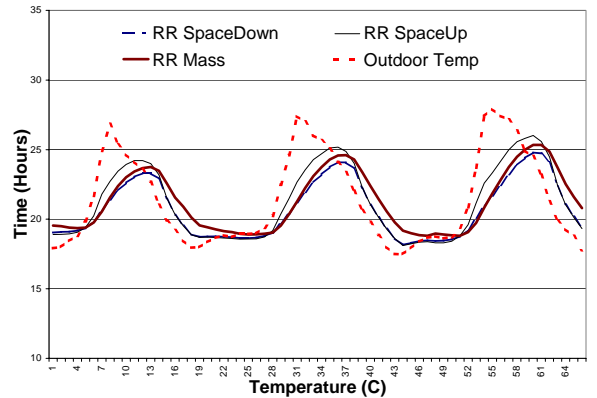


Figure 6: Three day section of series 5

DISCUSSION

Relationship of the System Performance with U_a

The series are compared with a variable that measures performance. This performance is determined by comparing the average reduction of the maximum temperature inside the cell with the average swing in the series as expressed in the following relation:

$$T_{\text{maxout}} - T_{\text{maxin}} / T_{\text{maxout}} - T_{\text{minout}} \quad (1)$$

Where:

- T_{maxout} : maximum temperature outside
- T_{maxin} : maximum temperature inside
- T_{minout} : minimum temperature inside

This means that the performance as calculated in this paper is equal to the reduction of the maximum temperature over the swing. The numerator expresses the reduction of the maximum temperature and the denominator is the outdoor swing. For this equation to be valid there must be a good correlation between the outdoor swing and the reduction of the outdoor dry bulb temperature as is the case of all series, but for lack of space only series 1 is presented (Fig 7).

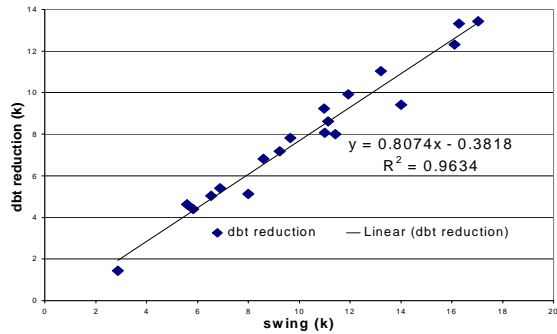


Figure 7: Correlation between the reduction of the dry bulb temperature and the dbt swing in series 1.

The closer to one, the better the cooling system This performance can also be expressed as a percentage where 100% would be the maximum performance. The performances at the upper and lower levels inside the cell and the differences between the two are presented in table 3.

Table 3. Series Performances: dbt drop/outdoor swing (%)

Series Number	Space Down	Space Up	Difference
1	77.04%	71.06%	8.42%
2	52.05%	44.70%	16.43%
3	69.49%	59.29%	17.20%
4	69.59%	58.43%	19.10%
5	40.29%	30.57%	31.79%

Since the series were performed at different times of the year in Los Angeles (34 North Latitude), and the radiant system operates automatically from sunset to sunrise, a correction factor had to be introduced to account for the effect of the different duration of the nights and day. This factor is calculated by determining the number of night hours in the midpoint of the series as a function of a 12 hour night using the following equation:

$$P = 1 - (HN/12)$$

Where:

P = A percentage that must be applied to the performance factor to adjust for a different day to night ratio. A positive number indicates that the series had nights shorter than 12 hours and a negative number that the series had nights longer than 12 hours.

HN = number of hours of night in the midpoint day of the series

For the five series, the adjustment factors are -8% in series 1, 17% in series two, - 25% in series 3, a - 21% in series 4, and 4% in series 5.

Before adjusting for the day to night ratio there is not a good fit between the winter series with longer nights (series 3 and series 4), and the summer series with shorter nights (series 1, 2 and 5) (Fig 8). In series 1, 3 and 4 there are more night hours than daylit hours so the system is working for a longer time and the adjustment factor must reduce the performance. In series 2 and 5 the duration of the night is shorter and the adjustment factor must increase the performance proportionally. After adjusting for the day to

night ratio a better linear relationship can be established between the increase in the heat gain coefficient and the reduction in performance (Fig 9).

Table 4. Series Performances: dbt drop/outdoor swing (%) adjusted for day to night ratio

Series Number	Space Down	Space Up	Difference
1	70.62%	65.14%	8.42%
2	60.73%	52.15%	16.43%
3	52.12%	44.47%	17.20%
4	55.09%	46.26%	19.10%
5	41.97%	31.84%	31.79%

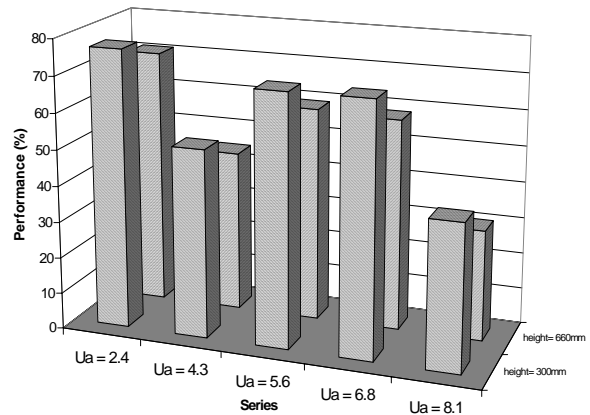


Figure 8: Performance of the different series without adjustments.

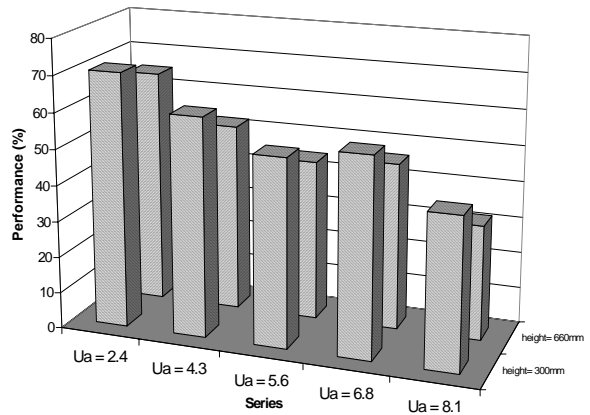


Figure 9: Performance of the different series after adjustment for day to night ratio.

Regression analysis permits us to determine predictive equations as a function of the heat loss coefficient (Fig 10, 11). The performance of the system at a height of 660 mm can be predicted with the following equation:

$$Y = -5.27x + 76.6 \quad R^2 = 0.92$$

And at a height of 300 mm:

$$Y = -4.57x + 80.9 \quad R^2 = 0.91$$

In these equations **x** is the heat gain coefficient and **y** is the predicted performance.

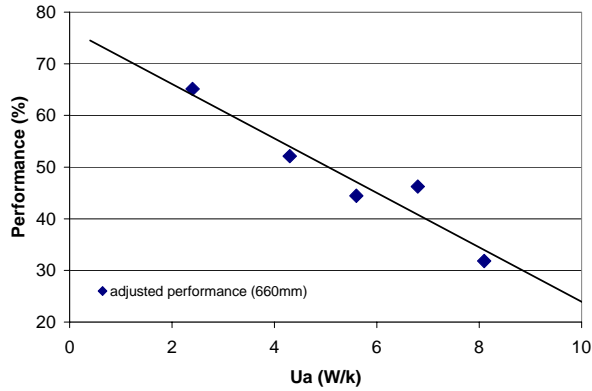


Fig 10: Correlation between the heat loss coefficient and the performance of the system at a height of 660mm

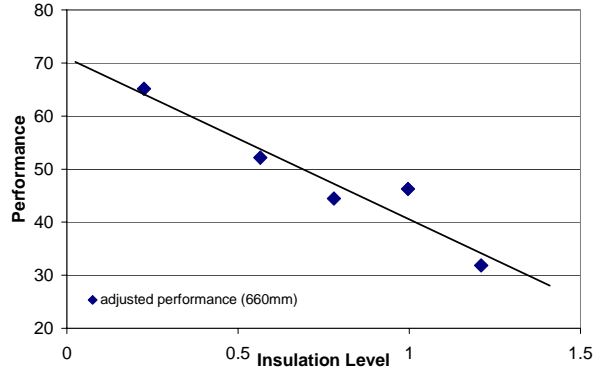


Fig 12: Correlation between the insulation level of the walls and the performance of the system at a height of 660mm

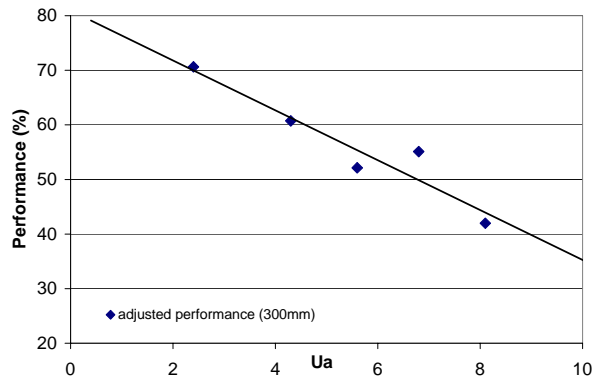


Fig 11: Correlation between the heat loss coefficient and the performance of the system at a height of 300mm

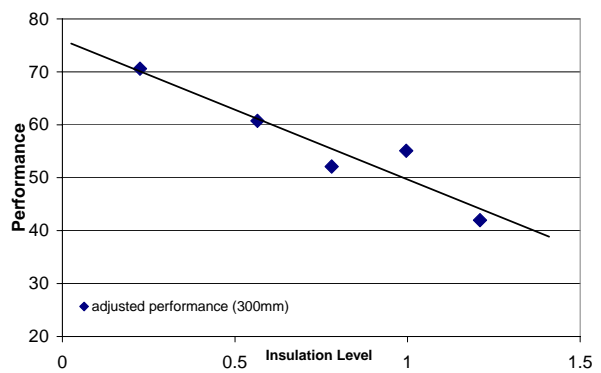


Fig 13: Correlation between the insulation level of the walls and the performance of the system at a height of 300mm

Relationship of the Performance with the Insulation Level

Since the roof and the operable ceiling are not modified, the performance of the system can also be expressed as a function of the insulation value of the wall:

At 660 mm:

$$Y = -30.43x + 71 \quad R^2 = 0.9184$$

At 300 mm:

$$Y = -26.34x + 76 \quad R^2 = 0.9$$

Where x is the U value of the wall in (W/m² K) and Y is the predicted performance of the system expressed as a percentage. The numbers 76 and 71 indicate the best possible performance of this system, 76% at the lower level and 71% at the upper level.

The slopes of the predictive equations are similar to those of the heat loss/performance figures but in this case as a function of the insulation level. These figures can also be used as graphic tools to determine necessary insulation levels for a desired performance. Following a horizontal line from the desired performance level until it reaches the diagonal will indicate the desired insulation or Ua values.

To determine the insulation level required for a desired performance, the previous equations are used, but determining x as a product of y.

At a height of 660mm:

$$X = (Y-71) / - (30.43)$$

At a height of 300mm:

$$X = (Y-76) / - (26.34)$$

The maximum possible performance for this system is 71% at a height of 660mm and 76% at a height of 300mm. Values higher than these produce zero or a negative U value which is impossible to accomplish. To determine the insulation level required for a performance of 50% at a height of 300 mm:

$$X = (50-76) / -(26.34)$$

$$X = 0.987$$

Thus if the U value of the walls is higher than 1 W/m²k, the performance of the system will be lower than 50%. This means that the reduction of the maximum temperature inside the cell will be less than 50% of the outdoor swing. This is a good rule of thumb to determine insulation levels of the walls to achieve a proposed indoor maximum temperature, as a function of the outdoor swing.

Differences between maximum temperatures at different heights

As the insulation value decreases and the heat loss coefficient increases, the difference in temperature, and thus in performance, between the upper and lower level increases. In the well-insulated cell the temperature difference between both heights is only 8.4 %, while with the lowest insulation value the temperature difference increases to 31.8 %. The reduction is not linear but rather seems to follow an exponential curve in the form:

$$Y = 0.0559 e^{0.2053x}$$

Where y is the predicted temperature difference between both levels and x is the heat loss coefficient (Fig 17).

For U_a values between 1 and 10, this roughly represent a 4% increase in the temperature difference between both levels for every unit increase in the heat loss coefficient.

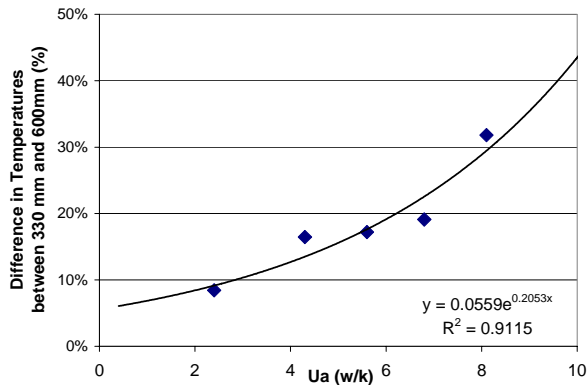


Fig 17: Correlation between the difference in maximum temperatures at 300 mm. and 600 mm. and the U_a

Relationship of the U_a with the Maximum Indoor Temperature at different Heights inside the Cell

The heights of 300 mm and 660 mm represent heights of 30% and 66% of the total height of the cell. If the reduction in temperature, up to the height of the mass is linear and related to the height, then an equation that predicts the reduction on performance at different heights up to the height of the mass can be proposed. For the lowest heat loss coefficient (2.4 w/K) the predictive equation is:

$$Y = -0.0152x + 75.187$$

And for the highest heat loss coefficient the equation is:

$$Y = -0.281x + 50.406$$

There is an approximate reduction of 1.5% in performance per 100mm height in the most insulated cell and a reduction of 2.8% in performance per 100mm elevation in height in the least insulated cell. Thus the temperature of the air increases more rapidly per unit of height in poorly insulated cells than in well-insulated cells, which maintain indoor temperatures at a more constant level at all heights.

There are other factors that can affect the heat loss coefficient, such as changes in the insulation levels due to seasonal differences and outdoor air velocity. The consideration of these factors would further refine the

prediction of the performance. In another paper in this conference (Givoni - La Roche) equations have been derived to predict the internal maximum temperature with the different heat losses.

CONCLUSIONS

The U_a value affects the thermal performance of the test cell, which simulates a radiantly cooled building which is closed and shaded during the daytime. The performance is also different at different heights inside the space, and the slope that defines the reduction of the performance is not the same at different heights. The reduction in performance as a function of U_a is more pronounced at higher levels inside the cell. Roughly, there is a linear decrease in performance of about 4.5% per every degree increase in the U_a coefficient at a height of 300mm and 5% per every degree increase in U_a at a height of 660mm. The predictive equations and charts that are presented in the paper permit to determine, either the required U_a to achieve a given performance, or the predicted performance of a radiant system, with similar design with a given U_a at different heights inside a building.

Experimental results indicate that the temperature swing inside the cell is related to insulation levels in the walls. Less insulation in walls generate a larger temperature swing.

The insulation level also affects the difference between the peak temperatures at different heights inside the space. With higher insulation values (less insulation), there is a larger difference between both values and with lower insulation values (higher insulation) the temperature distribution inside the space is more homogenous. Sufficient insulation or air movement for destratification must be provided to guarantee well distributed temperatures inside the cell.

This system is more effective as the length of the night increases and would be especially effective in hot weather spells during the Fall or Spring seasons of medium-low latitudes such as the South Western United States or many Mediterranean cities. With longer nights insulation levels can also be reduced because the performance of the system improves.

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