EFFECTS OF THERMAL MASS, SMART SHADING AND SMART VENTILATION ON INDOOR TEMPERATURE

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RESUMEN

Se desarrolló un prototipo de termostato que permite controlar sistemas en un edificio comparando diversas variables. Esta ponencia presenta los resultados de varias series experimentales en el verano del 2004 en las cuales el termostato controla al extractor de aire y las persianas en una celda. Se realizaron varias series con diversas cantidades de masa y se presenta una ecuacion que permite determinar la temperatura maxima promedio en el interior del espacio a partir de las temperaturas máximas y mínimas promedio del exterior y la cantidad de masa termica en el interior.

ABSTRACT

A prototype microcomputer-controlled thermostat that can control different systems in a building by measuring indoor and outdoor temperature was developed. This paper presents results of several series with the controller operating both a whole-house fan that optimizes cooling with outdoor air and a window shading system. This paper also quantifies the effects of modifying the amount of thermal mass on indoor comfort when using this controller and presents a simple equation that permits to determine internal maximum temperature as a function of outdoor swing and thermal mass.

INTRODUCTION

A passive cooling system is capable of transferring heat from a building to various natural heat sinks. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates. It occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Night ventilation reduces internal maximum temperatures, peak cooling loads, and overall energy consumption.

In previous papers a smart controller that optimizes the use of forced ventilation for structure cooling in a building was tested (La Roche & Milne 2001, 2002). This controller uses a set of decision rules to control a fan to maximize indoor thermal comfort and minimize cooling energy costs using outdoor air, a great source of free cooling energy. This controller knows when to turn the fan on and off to cool down the building's interior mass so that it can 'coast' comfortably through the next day, reducing the need for air conditioning.

There is agreement on the fact that heat gains by conduction through the building fabric, solar gains through window glazing, infiltration from warm outdoor air and internal gains from equipment and occupants must be reduced for nocturnal ventilative cooling to be effective. The ability of this smart system to cool with natural ventilation can be seriously compromised if certain design considerations are not taken into account regarding the amount of mass and the control of solar radiation. This was documented in previous papers (La Roche & Milne, 2003, 2004).

There are also climatic parameters that determine the effectiveness of nocturnal ventilative cooling: the minimum air temperature, daily temperature swing, and water vapor pressure level, (Geros et al, 1999).

A smart system that reduces the heat load through windows, while increasing the performance of the cooling system by ventilation, should be more efficient that one that controls only one of these. This paper discusses the effect of both smart ventilation and smart shading on indoor temperature.

2. EXPERIMENTAL SYSTEM

The experimental system consists of a microprocessor controller connected to thermistors that measure temperature, a laptop computer connected to it which contains the control programs and collects and stores experimental data, the two test cells and an active ventilation system, which consists of a 4-inch inlet and on the outlet side a four-inch fan that is turned off or no depending on ventilation needs (Fig. 1).

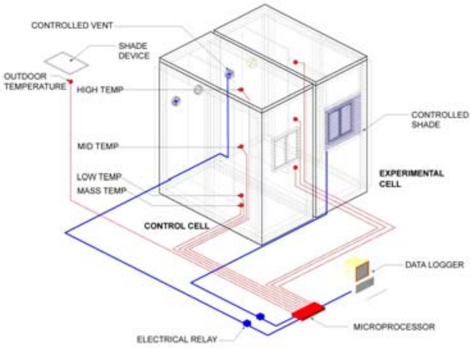

Fig. 1 The experimental system

The test cells are identical and built with the characteristics of typical California slab-on-grade houses. Only the characteristics that could affect the thermal performance of the ventilation system where incorporated in the cells: the insulation level, the brick slab and the glazing. Another simplification was that the cells only had a south-facing window so that they would receive the same amount of radiation at the same time. The cells are 122 cm. (4 ft.) wide by 244 cm. (8 ft.) long and 244 cm high, and are oriented with the longest facade towards the east and west. The cells have 7.6 cm (3 in) foam R12 insulation on the outside and 6.4mm (¼ in.) gypsum board inside the walls and roofs with a U value of 0.43 W/m^{2}K in the walls. The east and west walls have additional shading provided by an insulation panel separated 8 cm from the wall. A calibration series, with both cells in identical conditions demonstrated that these panels eliminated the distortion caused by solar radiation in the morning and afternoon. The floor is hardboard placed on top of an insulation panel and the roof has two layers of insulation with a U value of 0.22 W/m^{2}K. There is a 61 x 61 cm (2 x 2 ft) double pane window on the south side with a Solar Heat Gain Coefficient of 0.72 and a U value of 4.25 W/m^{2}K (0.75 Btu/h ft^2 °F). The area of the window is .37 m^2 (4 ft^2) for a ratio of the glazing to floor area of 12.5%. The walls and windows are carefully sealed so that infiltration is controlled only by the fan and damper system. Each cell has cement bricks distributed evenly in the floor simulating a concrete slab. The bricks are spread over the surface of the floor in different amounts as required for the different series.

There are four thermistors in the experimental cell, three thermistors in the control cell and one thermistor outside in the shade. In each cell the thermistors are placed in the center of the cell, but at different heights. The lowest one is 5 cm (2 in) above the bricks, the middle one is 137 cm (54 in) and the highest one is 231 cm (91in), which is 10 cm below the ceiling. In the experimental cell an additional thermistor measures the temperature of the mass. Only air temperature at a height of 137 cm is reported in this paper.

Fig. 2 The experimental and control cells viewed from the south

One of these cells, with the smart operable venting system and the smart shading system is the "experimental" cell in which the air change rate varies between 0.7 and 15 air changes per hour and the shade varies from completely open to completely closed. The other cell is the "control" cell with a fixed ventilation rate of 0.7 air changes per hour.

Various control strategies were tested in the summers of 2000 and 2001 with different relationships between the air change rates, and values for comfort low and comfort high, and presented in another paper (La Roche & Milne, 2002). The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell is indicated in equation (1)and was used for these series in 2004.

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* fan ON else fan OFF
[Eq. 01]

Where:
t_o = temperature outside
t_i =temperature inside
C_{f_low}, = comfort low at 18.33 °C (65 °F)
C_{f_high} = Comfort high at 25.55 °C (78 °F).

This rule was already tested to determine the effects of internal mass and window size on thermal comfort (La Roche & Milne 2003, 2004). Now instead of having fixed window sizes, the effects of a controller that also changes the amount of shading according to a predetermined rule [Eq. 02] are presented. The rule that is used for this controller is:

If 70 F < t_i *then* Shade Down else Shade Up.
[Eq. 02]

3. EXPERIMENTAL RESULTS

Eight series have been tested to explain the effects of modifying the amount of mass on the smart shading and venting systems (Table 1). Four series have the blinds outside the window and four series have the blinds inside. Each of these four series had different amounts of mass inside the test cell equivalent to 75, 150, 225 and 300 kg/m^2. The control series always has the shade open and the fan off with constant mass, 150 kg/m^2.

Table 1: Tested series presented in this paper

Series	**Description**
1. SHADE INSIDE LOW MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Inside 75 kg/m^2
2. SHADE INSIDE MED MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Inside 150 kg/m^2
3. SHADE INSIDE MED-HIGH MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Inside 225 kg/m^2
4. SHADE INSIDE HIGH MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Inside 300 kg/m^2
5. SHADE OUTSIDE LOW MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Outside 75 kg/m^2
6. SHADE OUTSIDE MEDIUM MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Outside 150 kg/m^2
7. SHADE OUTSIDE MED-HIGH MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Outside 225 kg/m^2
8. SHADE OUTSIDE HIGH MASS	Experimental: Fan ON 0-15 Air changes Hour Shade ON Outside 300 kg/m^2

3.1. Series 1: Shade Inside & Low Mass

In the first series, initiated in September 16, 2004, the shade system is inside the window and the cell has 166 kg mass in the slab equivalent to 75 kg/m^2. As in all the series, the smart ventilation and shading systems are operating in the experimental cell and off in the control cell. In figures 3 through 10 the smart shading system is indicated by the solid area, in a scale from 0 to 100%, and the air change rate is indicated in average air changes per hour in the solid bars in a scale from 0.7 to 15.

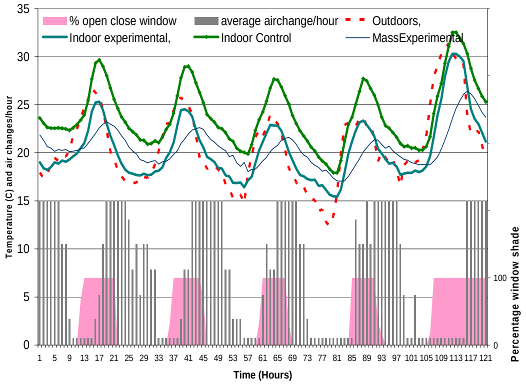

Fig. 3 Series 1, shade inside and low mass (75 kg/m^2)

3.1. Series 2: Shade Inside & Medium Mass

In the second series, initiated in September 10, 2004, the shade system is inside the window and the cell has 332 kg mass in the slab equivalent to 150 kg/m^2.

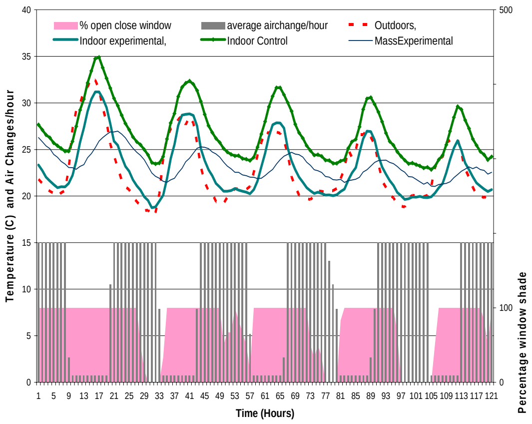

Fig. 4 Series 2, shade inside and medium mass (150 kg/m^2)

3.2. Series 3: Shade Inside & Medium-high Mass

In the third series, initiated in August 13, 2004, the shade system is inside the window and the cell has 498 kg mass in the slab equivalent to 225 kg/m^2.

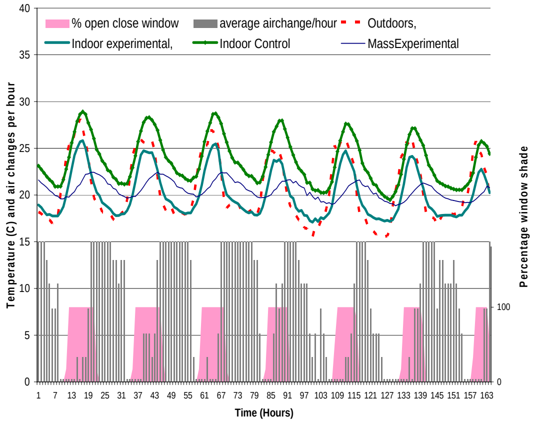

Fig. 5 Series 3, shade inside and medium-high mass (225 kg/m^2)

3.3. Series 4: Shade Inside & High Mass

In the fourth series, initiated in September 2, 2004, the shade system is inside the window and the cell has a mass in the slab of 664 kg equivalent to 300 kg/m^2.

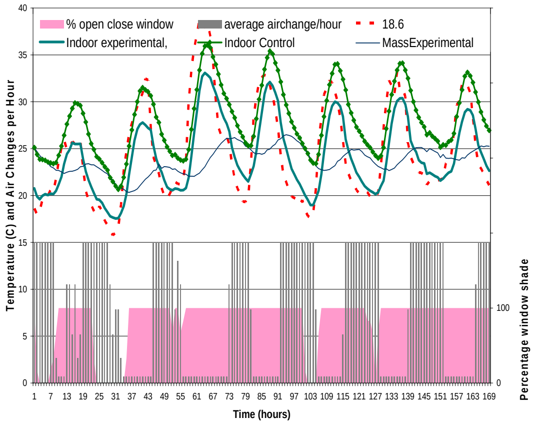

Fig. 6 Series 4, shade inside and high mass (300 kg/m^2)

3.3. Series 5: Shade Outside & Low Mass

In the fifth series, initiated in September 22, 2004, the shade system is outside the window and the cell has a mass in the slab of 75 kg/m^2.

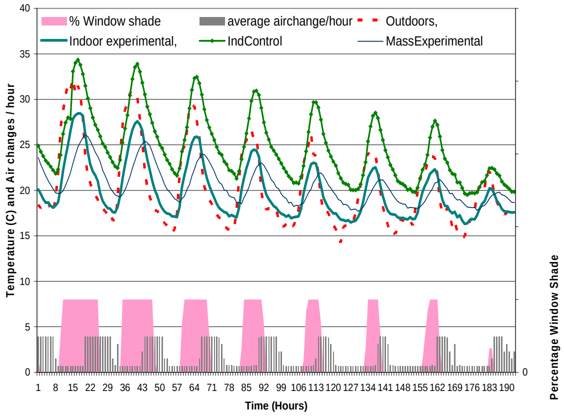

Fig. 7 Series 5, shade inside and low mass (75 kg/m^2)

3.3. Series 6: Shade Outside & Medium Mass

In the sixth series, initiated in July 9, 2004, the shade system is outside the window and the cell has a mass in the slab of 150 kg/m^2.

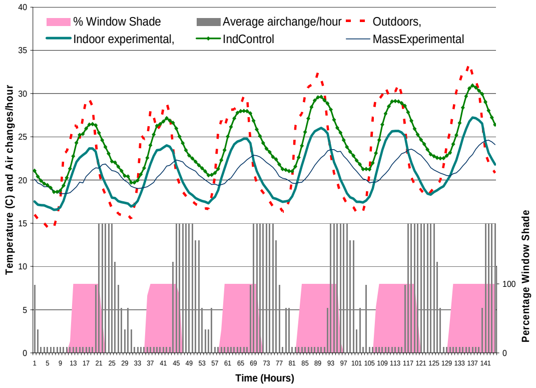

Fig. 8 Series 6, shade inside and medium mass (150 kg/m^2)

3.3. Series 7: Shade Outside & Medium-High Mass

In the seventh series, initiated in August 6, 2004, the shade system is outside the window and the cell has a mass in the slab of 225 kg/m^2.

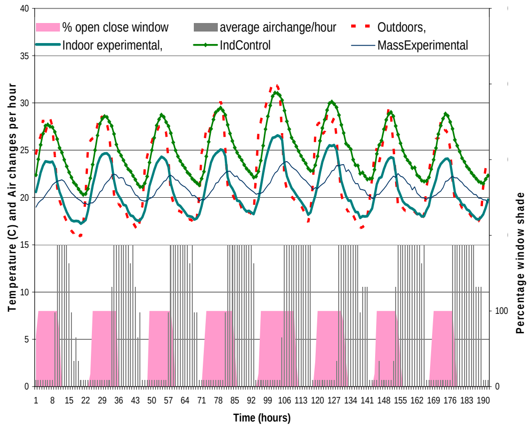

Fig. 9 Series 7, shade inside and medium-high mass (225 kg/m^2)

3.3. Series 8: Shade Outside & High Mass

In the eight series, initiated in July 23, 2004, the shade system is outside the window and the cell has a mass in the slab of 300 kg/m^2.

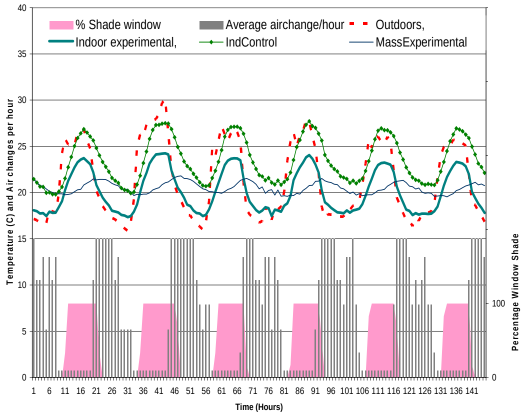

Fig. 10 Series 8, shade inside and high mass (300 kg/m^2)

4. DISCUSSION

The Temperature Difference Ratio (TDR) is used to evaluate the performance of the different variables. Then predictive equations are developed that permit to determine the maximum temperatures inside test cells with different mass configurations.

4.2. Temperature Difference Ratio

The eight tests are compared with each other using a ratio called the Temperature Difference Ratio (TDR). The TDR normalises the capacity to reduce the indoor maximum temperature, which in this case is defined by differences in mass as a function of the outdoor swing, permitting comparison of the different series with each other. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations (La Roche & Givoni, 2002, La Roche & Milne 2003, 2004). TDR is calculated using the following equation:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \quad \text{[Eq. 03]}$$

Where:

TDR= Temperature Difference Ratio

T_{maxout}= Maximum temperature outside

T_{maxin}: Maximum temperature inside

T_{minout}: Minimum temperature inside

The numerator is the difference between the indoor maximum temperature and the outside maximum, and the denominator is the outdoor swing. The higher the TDR, the better the cooling performance of the system. A higher value indicates that there is a larger temperature difference between outdoors and indoors and thus more cooling. In a naturally ventilated building the result of this division can't be higher than 1.0.

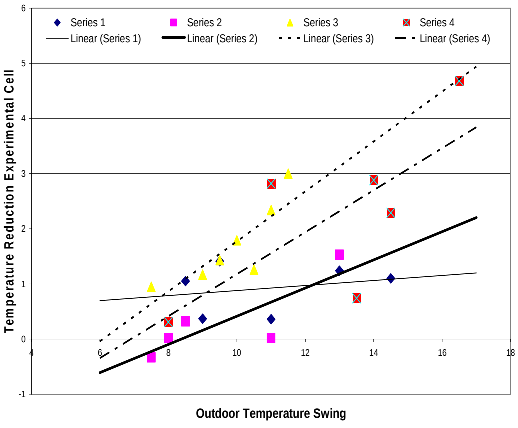

Fig. 11 Correlation between the daily outdoor temperature swing and the daily TDR in the experimental cell in series 1, 2, 3, 4 (shade inside).

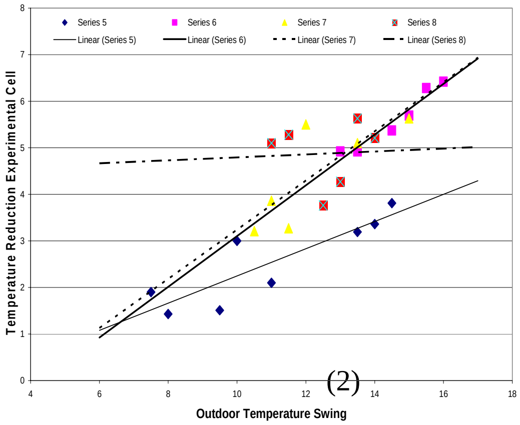

Fig. 12 Correlation between the daily outdoor temperature swing and the daily TDR in the experimental cell in series 5, 6, 7, 8 (shade outside).

For this equation to be descriptive of the building performance there has to be a correlation between the outdoor swing and the difference between the indoor and outdoor maximum temperatures (Figs. 11 and 12). Each point in figures 11 and 12 is one day's data, comparing the difference between the indoor and outdoor maximum temperature with the outdoor diurnal temperature swing. Figure 11 shows data for the four series with the shade inside and figure 12 shows the data for the four series with the shade outside. A separate trend line is plotted for each series. In all series, the TDR increases as the swing increases.

After proving that there is a correlation between the swing and the TDR, the TDR is calculated for each day of the different series and averaged for each one. The eight series are plotted in figure 13, which correlates the amount of mass (kg/m2) in the floor slab with the TDR. One trendline is plotted for the series with the shade inside and another for the series with the shade outside. The series for the shade outside has higher TDR values. Only the series with the shade inside and the highest amount of mass has a TDR value higher than a series with the shade outside.

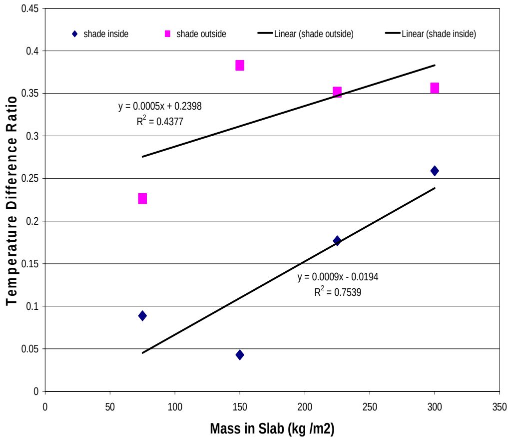

Fig 13 Correlation between the floor mass and the TDR performance in the test cells with a smart ventilation and shading system.

The equations that predict the TDR as a function of the amount of mass are:

$$TDR_{shdout} = 0.0005 * Mass + 0.2398 \quad \text{[Eq. 04]}$$

$$TDR_{shdin} = 0.0009 * Mass - 0.0194 \quad \text{[Eq. 05]}$$

Where:
TDR_{shdout} = TDR with the shade outside
TDR_{shdin} = TDR with the shade inside
Mass = Floor slab mass kg/m^2

Equations 4 and 5 predict TDR as a function of the amount of mass (in kg/m^2) in the slab. Four series help to determine each predictive equation, one for each mass amount tested. Each of these points is the average TDR of a six day series, for a specific amount of mass. The TDR with the shades outside is an average of .22 better when the shades are inside for the same amount of mass.

4.3. Prediction of Maximum Temperatures using the Temperature Difference Ratio

TDR can be calculated using equations 4 and 5 which are selected depending on the position of the shade (outside or inside). Equation (3) permits to determine the indoor temperature as a function of the daily swing and the amount of mass in the slab.

Since

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout})$$

then

$$T_{maxin} = T_{maxout} - [TDR * (T_{maxout} - T_{minout})]$$

This equation can be used in well insulated buildings that have smart controllers for ventilation and shading.

It is then a simple matter to predict the indoor maximum temperature when the outdoor daily swing and the amount of mass in the building are known. The measured and predicted daily maximum temperatures in series 7 are shown as an example (fig 15).

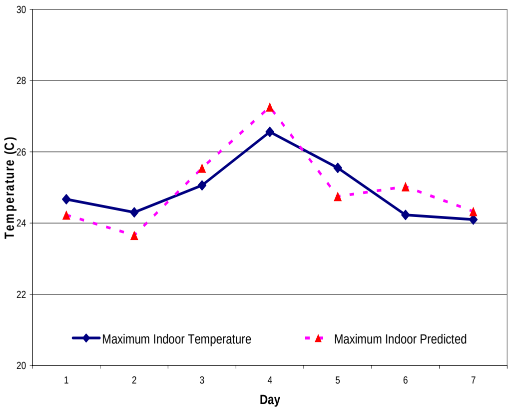

Fig 15 Measured and predicted daily maximum average temperatures in the experimental cell in series 7.

Applying the equation to Maracaibo, a city in a warm and humid climate, with a summer maximum average outdoor temperature of 32.8 C and an average daily swing of 9.2 C the maximum predicted temperature inside a building with 300 k/m2 of mass in the slab would be 29.21 C, which depending on the relative humidity could be inside the comfort zone with natural ventilation. If we reduce the amount of mass to 75 k/m2, the maximum temperature inside the cell would be 30.2 C. Because of the small daily swing, the difference between the maximum temperatures with different masses is not notable, but it is still possible to use a combination smart shading and venting system to improve comfort, in warm humid climates.

In more temperate summers like in Los Angeles with average maximums of 29 C and a swing of about 17 C in a cell with 225 k/m2 of mass, the maximum indoor temperature would be 23 C.

In the hot and dry summer of Phoenix, Arizona with a maximum of 42 C and a swing of 23 C, inside a building with 350 k/m2 the maximum indoor temperature would be 32.4 C.

4.3. Prediction of Maximum Temperatures as a function of the Slab Thickness

Assuming a density of concrete of 2400 k/m3, equations 4 and 5 can be plotted as a function of slab thickness:

$$TDR = 1.1467 * T + 0.2398$$
[Eq. 06]

$$TDR = 2.0648 * T + 0.0194$$
[Eq. 07]

For lightweight concrete (D=1750 kg/m3):

$$TDR = 0.0084 * T + 0.2398$$
[Eq. 08]

$$TDR = 0.0151 * T -0.0194$$
[Eq. 09]

5. CONCLUSION

Sets of equations have been developed to predict maximum indoor temperatures with specific amounts of mass or to determine the minimum amount of mass needed to achieve an indoor temperature below a specific value.

This paper demonstrates that it is possible to use a smart thermostat that controls blinds and fans to reduce the maximum temperature inside a test cell as compared to the outdoor temperature. These tests also confirm that more mass with the blinds outside the window performed better than less mass with the blinds inside.

More tests have to be done, especially with larger amounts of mass but preliminary tests seem to validate these equations and could help determine the limits of the comfort zone with ventilation in shaded buildings with smart ventilation. If this equation is valid we can assume that smart ventilation and shading systems can help to reduce indoor maximum temperatures in insulated buildings, with some thermal mass in warm climates.

6. REFERENCES

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