Research Communication

The thermal behavior of a concrete 'finned' wall in a hot-arid zone

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Abstract

The thermal behavior of an exposed concrete slab with a grid of truncated pyramids on its outer surface was found to differ considerably from that of a similar slab with a smooth outer surface, under hot-arid conditions. When the slab was placed vertically facing south (simulating a south-facing wall), the three-dimensional geometry of its exterior reduced radiative heat gain. Placed horizontally, radiative heat gain increased. Painting the slabs white reduced the relative contribution of radiative heat gain, while the increased surface area resulted in the creation of a thick 'boundary' layer that affected the thermal behavior of the slab under certain conditions.

1. Introduction

The heat exchange processes occurring at the external surfaces of buildings have been studied extensively. Heat is transferred between the surface of the thermal mass and its environment, mainly by radiation and convection, while the heat transfer taking place within the bulk of the material is purely conductive. Assuming that the ambient conditions are different from the internal ones and that they are transient in nature, the heat transfer in a wall having thermal mass and a finite resistance to heat flow consists of a fluctuating component (due to the thermal storage effect), superimposed on the steady-state heat flow through it.

Analytical description of these heat exchange processes has usually dealt with the general case of a wall (or ceiling) having the form of an infinite slab, thus simplifying the mathematical models. Where it is required to study more realistic conditions, numerical methods are used to provide computer simulations (Akbari *et al.* [1], for example). However, even though Oke [2] noted the effect of surface geometry in radiation exchange, and Gupta [3] described the effect of increased surface area on the thermal performance of a wall in Jaisalmer, investigation of non-planar wall surfaces has so far been limited.

A *preliminary* experiment was carried out to investigate the effects of altering the surface geometry of a building element on the heat flux through it. The basically planar surface form was replaced by a three-dimensional form, thus modifying both radiative and convective heat transfer between the surroundings and the building element, as well as the pattern of conductive heat flow inside the building material.

2. Experimental setup

Two concrete slabs were prepared, each one square meter in area, and *having identical mass*. Slab A, which served as the control, had a flat surface and a uniform thickness of 15 cm. Slab B had a 'finned' surface, created by an array of square truncated pyramids, 10 cm high and having a base of 8 cm$\times$8 cm and top of 6 cm$\times$6 cm. (This section was chosen in order to facilitate the extraction of the mold.) The pyramids were 2 cm apart at their bases, and the whole array projected from a 10-cm-thick slab (Fig. 1). Both slabs were insulated with 5-cm-thick expanded polystyrene board on all surfaces except the one being compared, and encased in a wooden frame 20 mm thick to facilitate handling. It is important to emphasize that both slabs contained an identical amount of concrete and thus had the same thermal capacity, the only differences being in their geometry and their exposed surface area.

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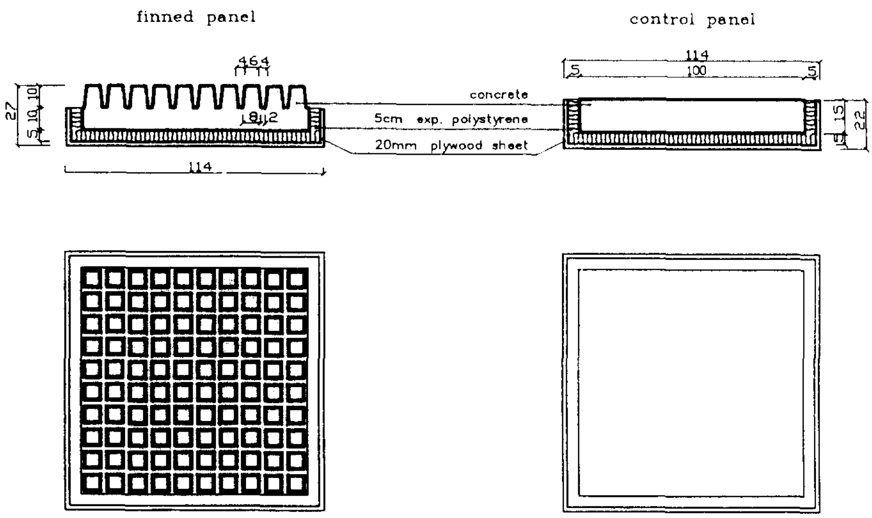

Fig. 1. The experimental panels.

The slabs were placed side by side in the test facilities of the Desert Architecture Unit in Sede-Boqer, Israel, between July 19 and October 3, 1988. The Sede-Boqer Campus is located at 30.8°N latitude, 500 meters above sea level. The climate is considered hot and dry during the summer: the average daily temperature is 24 °C, with an average maximum temperature of 32 °C and a daily temperature fluctuation of about 18 °C. Solar radiation is very strong, and may reach 27.5 MJ m^{-2} day^{-1}, on a horizontal surface (during June and July). In the summer, the relative humidity is very low, between 20–40% during most of the day, but it rises considerably during the night, when the ambient temperature drops sharply, to reach 90%.

The panels were exposed to the sun continuously during this period, in four different configurations:

(a) both panels in the vertical position, facing due south; the concrete surface was left in its natural grey color;

(b) both panels in the horizontal position; the concrete surface was left in its natural grey color;

(c) both panels in the horizontal position; the concrete surface was painted white;

(d) both panels in the vertical position, facing due south; the concrete surface was painted white.

Temperature readings were taken at the back of the panels, between the concrete and the polystyrene insulation. Ambient dry bulb temperature was measured in a standard meteorological station. All readings were made using PT-100 sensors and recorded at 3-min intervals, from which 15-min averages were calculated. The data was logged on a Data-Trapper model 1806 manufactured by Z.L. and Co. Electronic Industries Ltd., Israel, and processed using a Symphony software package.

3. Results

In all configurations of exposure, both panels exhibited a markedly smaller daily temperature amplitude than the ambient air, being 8–12 °C cooler during the daytime and 4–6 °C warmer at night. This was due to the large thermal mass of the concrete. However, there were also some significant differences in the thermal behavior of the two panels, which may be attributed to the response of the panels to the modes of exposure investigated:

3.1. Panels vertical, natural grey concrete

The most significant difference between the panels was that, throughout the daylight hours, the temperature measured at the back of the finned panel was lower by 2 °C than that measured at the back of the control panel (Fig. 2). The temperature gap was closed within an hour after sunset, so that by 20:00 nearly identical temperatures were recorded at the back of both panels. This condition remained unchanged throughout the night. In the morn-

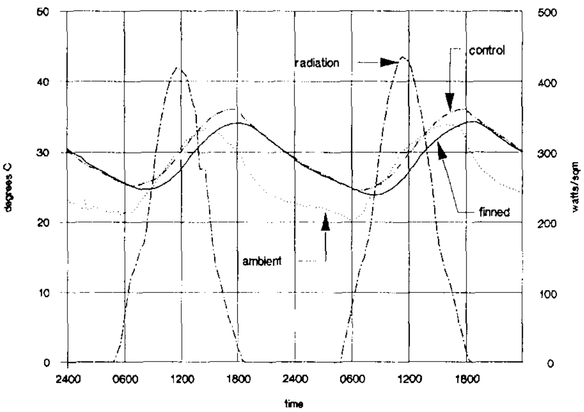

Fig. 2. Panels vertical, natural grey, July 28–29, 1988. —— finned panel; ····· ambient dry bulb temperature; – ·· – · control panel; – · – · global radiation W/m^2.

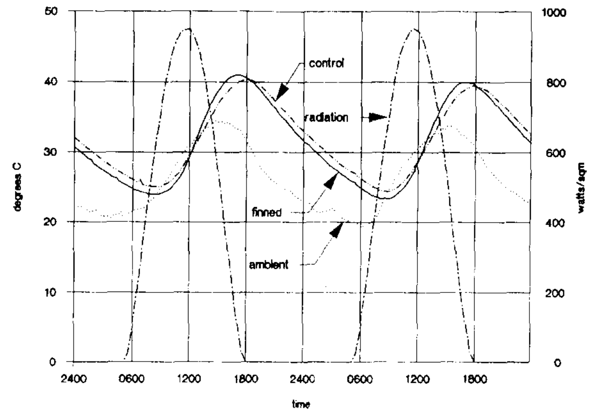

Fig. 3. Panels horizontal, natural grey, August 13–14, 1988. —— finned panel; ····· ambient dry bulb temperature; – ·· – · control panel; – · – · global radiation W/m^2.

ing, temperatures at the back of the finned panel continued falling for over two hours after the ambient air temperature started rising. The control panel exhibited a time lag of less than one hour, so that a difference of 2 °C was established relative to the finned panel by 10:00. The temperature reading in both panels peaked 3–4 hours after the maximum ambient temperature was recorded (generally around 15:00), the finned panel again showing a slightly greater time lag. The maximum temperature recorded for the finned panel was 2 °C lower than that of the control panel, and was about equal to the ambient maximum.

3.2. Panels horizontal, natural grey concrete

The finned panel was cooler than the control panel by about 1 °C throughout the night and morning. About two hours after sunrise temperatures started rising at the back of both panels, increasing at a higher rate at the back of the finned panel (Fig. 3), rising to up to 2 °C higher than the control. Both panels were, on average, considerably warmer than the ambient air, and only during the morning were they slightly cooler.

3.3. Panels horizontal, painted white

The finned panel was warmer than the control panel by up to 7 °C, the minimum difference being about 2 °C at about 09:00, and the maximum at about 18:00 (Fig. 4). The finned panel displayed much greater rates of cooling during the night and heating during the day.

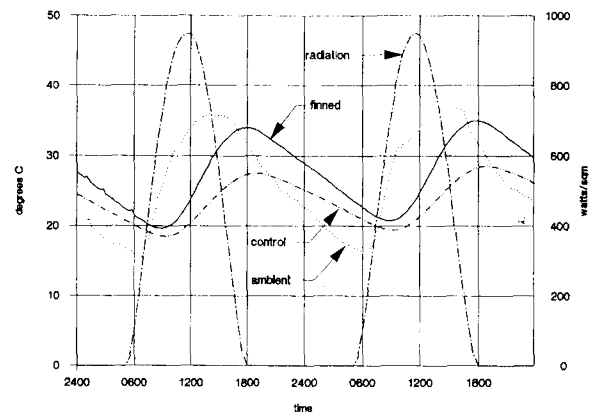

Fig. 4. Panels horizontal, painted white, September 4–5, 1988. —— finned panel; ····· ambient dry bulb temperature; – ·· – · control panel; – · – · global radiation W/m^2.

3.4. Panels vertical, painted white

The difference between the two panels was the smallest in this configuration. Daytime temperatures were nearly identical, and only towards the evening, at about 16:00, did the control panel start cooling slowly, opening up a difference of about 1 °C before the finned panel reached its peak about an hour later (Fig. 5). Temperature readings at the back of the panels reached a maximum that was about equal to that of the ambient air, but at a delay of 2–3 hours. The minimum was 3–4 °C higher than the ambient, with a delay of 2 and 3 hours for the control panel and the finned panel respectively.

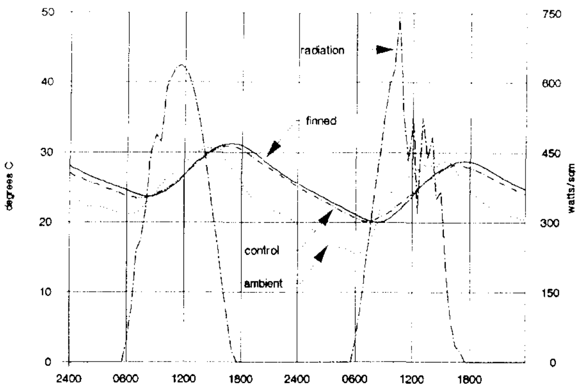

Fig. 5. Panels vertical, painted white, September 24–25, 1988. —— finned panel; · · · · · ambient dry bulb temperature; – · · – · control panel; – · – · global radiation W/m^2.

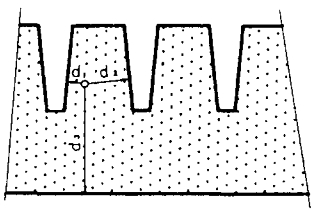

Fig. 6. Heat dissipating from a random point within the truncated pyramids.

4. Analysis of the results

The finned panel was designed to offset daytime radiative heat gains by increasing its convective losses. Radiation striking the exposed surface of both panels would in fact cause an increase in their temperature. However, in the finned panel, since energy would be dissipated through the sides of the pyramids, the amount of heat penetrating through to the back of the panel would be greatly reduced (Fig. 6). The distance from any point P within the truncated pyramid to the external surface of the panel (d_1, d_2) is smaller than its distance to the back (d_3). Thus, energy would first be dissipated through the sides rather than penetrate to the back. The surface temperature of the 2 cm gap between the bases of the pyramids would remain lower than the surface temperature of the control due to the fact that it is shaded by the pyramids throughout most of the day.

When the panels were placed in a vertical position facing south, and the concrete was left in its natural grey color, their thermal behavior was as predicted: during the daylight hours, when the radiative heat load was the greatest, the finned panel was cooler than the control panel.

When the panels were in a horizontal position, their surface still grey, results were markedly different. From about 10:00 till about 14:00, the temperature at the back of the finned panel rose faster than that at the back of the control panel. There are several explanations for this phenomenon:

(a) Since the panels were placed horizontally, the concrete base and the lower part of the truncated pyramids were struck by direct radiation, the sun being at an altitude of between 60° and 70° at this time (Fig. 7). The concrete between the pyramids in the finned panel was only 10 cms thick, vs. 15 cms in the control, (Fig. 1), so the incoming heat was conducted more easily to the back of the panel.

(b) Although the finned panel had a greater surface area, it also had a much thicker 'boundary layer'. In the case of the control panel, heat was removed by convection assisted by the relatively cooler ambient air moving freely on its planar surface. On the other hand, the pyramids of the finned slab panel trapped air between them, slowing the losses by convection.

Painting the panels white changed their behavior considerably. The daytime radiative heat load was reduced to such an extent that convection became the dominant heat gain mechanism.

In the horizontal position, the increased surface area of the finned panel also increased heat exchange between the concrete and the ambient air, relative to the control panel. The temperature of both panels was significantly lower than the ambient air throughout the

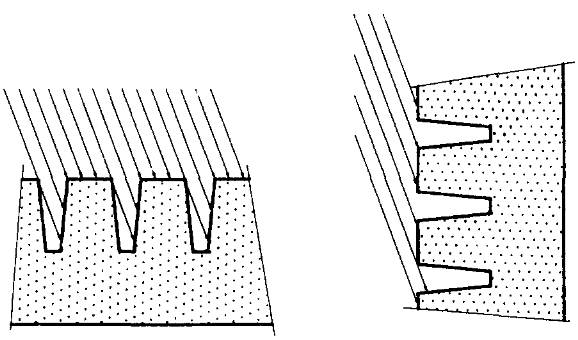

Fig. 7. Direct radiation at an angle of 70° striking the finned panel in the horizontal position (left) and in the vertical position (right).

daytime, and much higher than air temperatures during the night. Thus, high daytime air temperatures caused a greater rise in the temperature of the finned panel relative to the control. Similarly, low nighttime air temperatures caused a greater decrease in the temperature of the finned panel. As a consequence, the finned panel displayed a greater diurnal amplitude and a higher daily average than the control panel.

In the vertical position, the thermal performance of both slabs was very similar, the differences amounting to a maximum of about 1 °C. The dominant factor seems to be the thickness of a boundary layer created by the truncated pyramids. The exposed face of the panels was to the lee of the prevailing northwesterly winds, so that air trapped between the pyramids was undisturbed. This air created a boundary layer in the spaces between the pyramids, the thickness of which was about equal to their height. In the evening, as ambient temperatures dropped below that of the panels, the control began to cool almost immediately. The finned panel, though, was still affected by the warmer air of the boundary layer, and its temperature continued to rise for nearly two more hours. The opposite process occurred in the morning. While the control panel began to warm up almost as soon as temperatures started rising, the finned wall, under its blanket of cool night air, continued to cool down for another two hours.

5. Conclusion

Results of the *preliminary* investigation carried out indicate that articulation of the external surface of a building element will, by itself, alter its thermal behavior. Since the performance of the finned wall described was shown to be very sensitive to incident radiation, it is expected that the specific design of a building element making use of its properties will differ according to its orientation in the building. Further research is required to understand the effect of the non-planar surface on the convective heat exchange occurring in the modified boundary layer formed.

References

1 H. Akbari, D. Samano, A. Mertol, F. Bauman and R. Kammerud, The effect of variations in convection coefficients on thermal energy storage in buildings, Part 1—interior partition walls, *Energy Build.*, *9* (1986) 195–211.

2 T. R. Oke, *Boundary Layer Climates*, Methuen, London, 1978.

3 V. K. Gupta, Natural cooling systems of Jaisalmer, *Archit. Sci. Rev.*, *28* (3) (1985) 58–64.