THERMAL EFFICIENCY OF BUILDING CLUSTERS: AN INDEX FOR NON AIR-CONDITIONED BUILDINGS IN HOT CLIMATES

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Abstract

The thermal behaviour of common building forms is well known but this behaviour is altered when buildings are laid out in clusters. The overall building form, the extent of glazed and unglazed surface area, the building orientation and the proximity of other buildings determine solar heat gains to the building. A geometrical property of the building called solar exposure can be used to determine relative efficiency of different types of building clusters in both warm and cold climates. For air-conditioned and/or heated buildings the solar exposure bears a direct relationship to the energy used for heating and air-conditioning, but no such relationship exists between discomfort (or comfort) obtained in non air-conditioned buildings in warm climates and the building solar exposure. However, it is found that solar exposure per unit surface area of building is related to the discomfort index and the former is therefore a good indicator of the relative thermal performance of buildings in different urban layouts. Extended building forms with large external surface areas are useful in hot climates, but even better results can be obtained when compact forms are used with highly articulated surfaces.

Introduction

It is well known that thermal interaction between the internal environment of a building and the ambient conditions takes place through the building envelope. Since it is important to exclude unwelcome climatic extremes from buildings, the principles of good thermal design for temperate climates require:

1) a building that promotes solar heat gain,
2) a low surface to volume ratio to reduce conductive heat flow, and
3) a tight building envelope to reduce infiltration.

Correspondingly, for hot arid climates, thermal design principles call for:

1) a building form that intercepts least possible solar radiation,
2) a low surface area to volume ratio, and
3) a building design that promotes ventilation when needed.

In an earlier paper (Gupta, 1984b), a method for comparing the solar efficiency of archetypal building clusters called pavilion, court and street, was presented. The method used to determine relative efficiency was similar to that used by Knowles (1974), and it depended upon the calculation of ‘solar exposure’, a quantity which takes into account the area of irradiated surfaces of buildings as well as the variations in intensity of direct and diffuse solar radiation incident on each surface in the building cluster.

Taking a large building volume, a number of possible combinations of building clusters were analysed for solar exposure. These building forms had different external wall and roof areas, building depths and dimensions of internal partitions, while the window area taken as a fixed percentage of the floor area was equal in all the different forms. Solar heat gains to the building take place through the building fabric and through the windows. The actual heat gain to the building interior is reduced by the thermal resistance and thermal capacity of the envelope and by shades used over windows. Solar exposure would provide a good indication of the possible heat gains if the building was poorly insulated, had very lightweight external walls and roof or if it had large windows. For buildings with slightly better construction, it has yet to be seen if solar exposure is the critical factor that governs internal temperatures and potential energy expenditure.

In developing countries with a hot arid climate, yet another factor needs to be taken into account. Even though air-conditioning might be considered a necessity in these countries, it is normally not affordable and most buildings rely upon other methods for providing thermal comfort. The thermal behaviour of these non air-conditioned buildings is quite different from that of air-conditioned buildings as heat flows into the building during daytime while it flows out at night. The design principles for such buildings may have to be quite different from those for air-conditioned buildings.

Thermal analysis

Broadly speaking, there are two methods of predicting temperatures within buildings: (1) steady-state analysis, and (2) time-dependent analysis. The former can at best give very approximate

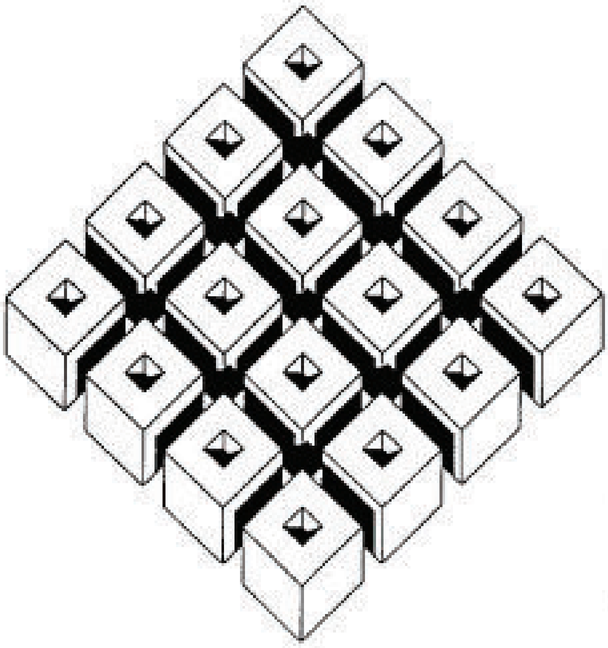

Figure 1. Momentary light and shade pattern of a building cluster

results with respect to temperature variations and is therefore useful only for heated buildings in temperate climates, while the latter takes into account heat storage effects associated with massive structures that are typical of hot regions. This can take various forms such as finite difference method, Fourier transform technique, response-factor method and the admittance procedure. Although the theory is well developed for each of these procedures, their accuracy in practice is limited by the unavailability of accurate data for important parameters like heat transfer coefficients, infiltration rates and even thermal conductivity. In the present context these parameters may not pose such a problem as they would affect the different forms in a similar manner. More important will be the variations in the pattern of sunlight and shade that occurs over the facades of buildings in a cluster (Figure 1). To account for such variations it is necessary to divide each building facade into a large number of small elements and to record and account for the diurnal lighting/shading pattern of each element separately. If the interaction between the different elements is considered, the calculations become very tedious and require a great deal of computer time.

Keeping in mind these inherent limitations in predicting internal temperatures, building forms can be simplified for comparison of thermal performance without any further loss in accuracy. In this study, the following assumptions are made:

1) Because of the difference in solar exposure, the thermal performance of blocks in a cluster will vary from the periphery where there is no shading, to the centre where there is shading. The average solar exposure of all the blocks is taken as the solar exposure of the typical block for the cluster. This condition is true for large clusters where edge effects are proportionately less.

2) The envelope of each block is represented by four parts with distinct thermal inputs: (i) the roof, (ii) wall areas that are sunlit during daytime, (iii) wall areas that are shaded during daytime, (iv) windows.

3) The variations in the relative proportion of sunlit and shaded wall areas are accounted for by adjusting the intensity of solar radiation while keeping the areas constant.

4) The entire thermal mass of the building (internal floor and wall partitions) is separated from the building envelope so that heat flow between the envelope and thermal mass takes place mainly by convection and radiation.

5) The space around the building, whether street or courtyard, is at a uniform temperature, even though it is known that in practice the courtyard temperature can be very different (Gupta, 1984a).

6) Radiative heat loss to the sky from the walls is proportional to the area of sky ‘seen’ by the wall.

The computations of indoor temperatures were made by using an analytical model which considers the periodic heat flow through the four building elements defined earlier, while the floor of the building is taken as a semi-infinite medium. The model ignores the effect of vapour pressure, and its output is the time-dependent temperature of the internal air.

Three building clusters (Figure 2), one each of pavilion, court and street types, have been evaluated. When choosing the physical configuration the total volume of the cluster was taken as 800,000 m3 corresponding to 266,666 m2 of floor area, the height of all buildings as 12m and the depth of building blocks approximately 10m. The distance between building blocks is half the height of the buildings. The physical and solar properties of the three clusters are given in Table I. Further it is assumed that the external walls are made of 25cm thick brick and the roof is 25cm thick concrete. Internal walls which occur at every 5m distance are 12cm thick and the intermediate floors are also 12cm thick. These building specifications are commonly used in India. The following analysis was carried out with temperatures and solar data for a hot summer day in New Delhi.

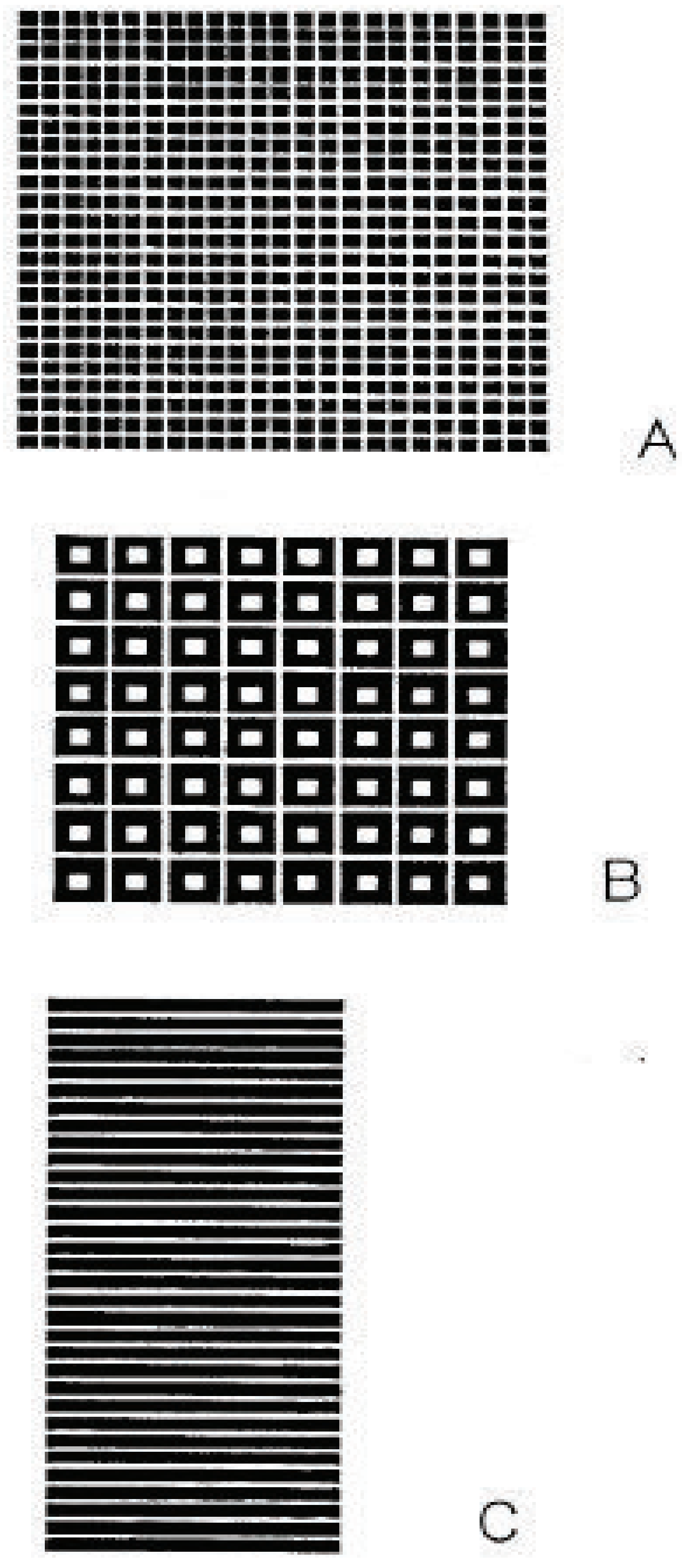

Figure 2. Three possible configurations of a given: building volume of 800,000m^3: (A) Pavilion, (B) Court, (C) Street. The first two are posiible housing layouts while the third represents institutional or commercial building.

	Pavilion	Court	Street
Physical Properties			
(a) Number of blocks in the cluster	576	64	32
(b) Height (m)	12	12	12
(c) Width of block (m)	10.76	10	10
(d) Length of block (m)	10.76	36.04	208.33
(e) Roof area (m^2)	66,668	66,668	66,668
(f) External wall area (m^2)	297,435	160,000	172,916
(g) Total external suraface area (m^2)	364,103	226,668	239,584
(h) Surface area/volume	0.45	0.28	0.30
(i) Internal partition area (m^2)	697,437	867,202	867,200
(j) Window area (m^2)	40,000	40,000	40,000
(k) Volume of buildings (m^3)	800,000	800,000	800,000
Solar Properties			
(a) Daily total summer solar exposure (m^2)	586,709	493,364	437,488
(b) Solar exposure/surface area	1.611	2.177	1.826
(c) Equivalent radiative loss area (with 6m street width) (m^2)	123,180	100,268	101,251

Table 1. Physical and Solar properties of three configurations of a given building volume

Thermal comfort index

The internal air temperatures obtained from this analysis are shown in Figure 3. These are shown under three conditions: (a) when there is no shading of windows and no ventilation in the building, (b) when 95% of window area is shaded and (c) when 95% of window area is shaded and the building is continuously ventilated with 6 air changes per hour. Since the temperatures show considerable fluctuation over the 24 hour period it is difficult to make a simple comparison. but it can be seen that the amplitude of temperatures is greatest for the pavilion and much less for the court and street. For a more accurate assessment of the energy required to bring the temperatures within comfortable limits, these have to be related to the human comfort range. Gupta and Spencer(1970) have suggested the use of a thermal discomfort index for unconditioned buildings where:

$$DISK = 1/N \left[\Sigma_{\text{day hours}} \frac{\left\{T_{ia} - T_c\right\}^+}{\Delta D} + \Sigma_{\text{night hours}} \frac{\left\{T_{ia} - T_{un}\right\}}{\Delta D} \right]$$

Where DISK = degree of discomfort

N = number of ordinated considered in a design cycle

T_{ia} = temperature of internal space, ^{0}C

T_c = daytime preferred temperature, ^{0}C

T_{un} = upper limit for night time comfort, ^{0}C

ΔD = deviation allowed in the day time (half of the range of comfort zone ^{0}C)

ΔN = deviation allowed in night time, ^{0}C

$+$ = only positive values to be considered, negative ignored

Because hourly temperatures are related to a preferred temperature, this index provides a good basis for comparison for building thermal performance. Since the summer temperature in non air-conditioned buildings does not go below the comfort range, the discomfort index can be modified to:

$$DISK = 1/N \left[\Sigma_{24\ hours} \left\{ T_{ia} - T_{uc} \right\}^{+} \right]$$

where T_{uc} is the upper limit of comfortable temperatures.

(The preferred summer temperature for Indian conditions is given as 27.5± 2.50C at 50% relative humidity. For non air-conditioned buildings the upper limit of thermal comfort is taken as 340C which is considered only moderately warm (Sharma, 1977).

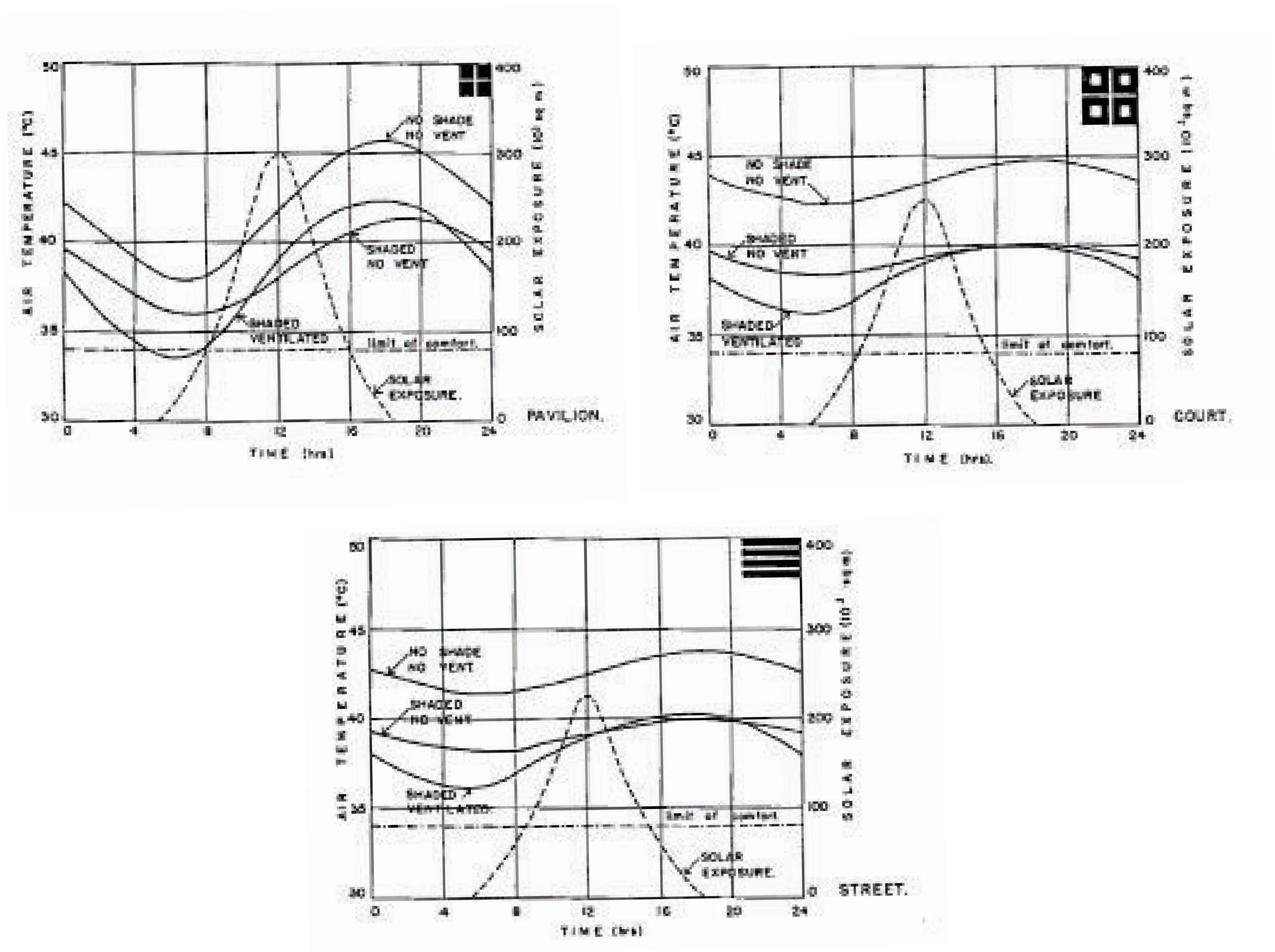

Figure 3. Air temperatures and solar exposures for building clusters

Building performance index

The discomfort indices so obtained for the three different conditions has been plotted against solar exposure in Figure 4. In each case it is seen that although the pavilion form has the highest solar exposure it has the lowest DISK value and the court form has the highest DISK value even though its solar exposure lies somewhere between the street and the pavilion. Furthermore, if the surface area of the pavilion is increased without changing its solar exposure- a condition which corresponds to articulation of the external surface (Figure 5) without changing the overall form-the DISK value is lower still. Clearly, solar exposure by itself is not an indicator of the thermal efficiency of a building form in a warm climate. There are other more influential factors which control the internal air temperatures.
As already noted, the three building configurations have many common features including volume, floor area, roof area and window area. The main difference lies in the extent of the external wall area. External surfaces transmit heat into the building, but in a warm climate these surfaces lose heat to the exterior as well. The usefulness of a particular arrangement of surfaces in a building depends upon the relative efficiency of these in allowing heat into and out of the building. In our case one can say that outward heat flow occurs through all the external surfaces and is therefore proportional to the area of these surfaces. Radiative heat gain, on the other hand, depends upon the solar exposure which is a measure of the area of the building exposed to the sun. Thus the efficiency of the building envelope can be related to the solar exposure per unit external surface area of the building. Figure 6 shows the DISK values for the three forms, plotted against solar exposure/surface area (SE/SA). There appears to be an almost linear relationship between DISK and SE/SA including the case of the articulated pavilion. Since solar exposure has the same units as surface area, we have here a non-dimensional indicator of the thermal performance of a building form for a hot climate. Knowles (1974) has used a similar indicator for a cold climate with the

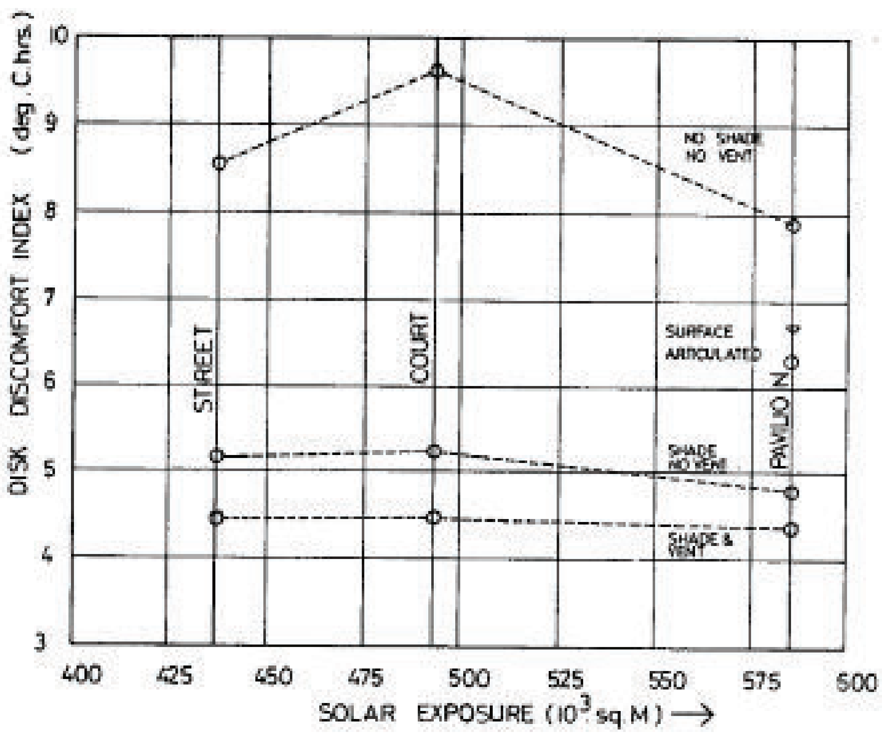

Figure 4. Discomfort index as a function of solar exposure

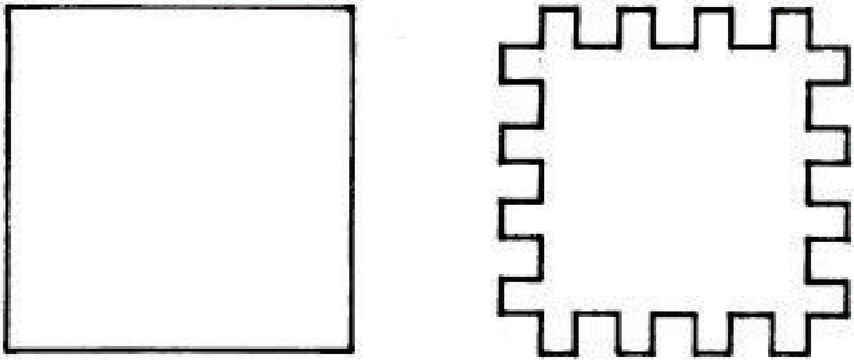

Figure 5. Surface area increase by articulation of building envelope

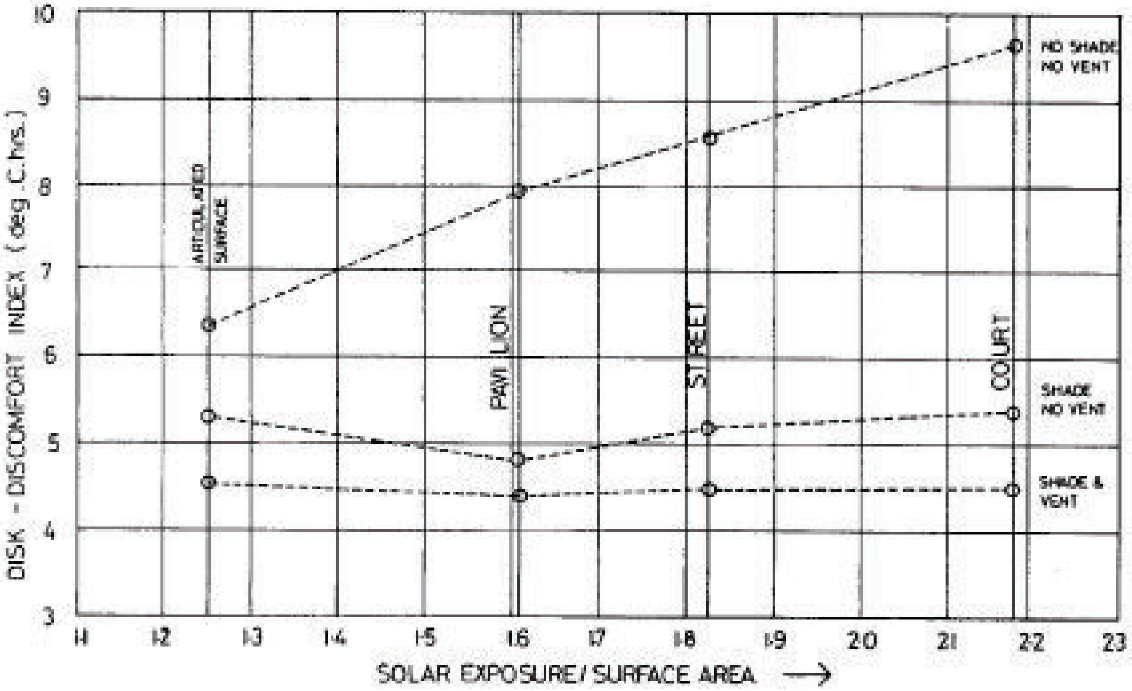

Figure 6. Discomfort index as a function of solar exposure per unit surface area

difference that a bigger SE/SA value means greater efficiency there.

The relative surface area and solar exposure properties of urban built forms were reported by Gupta (1984b), from which it is possible to choose forms with a particular range of surface area per unit volume, and to choose forms with a particular range of solar exposures. But it is a much more complicated and difficult task to choose a form with a low solar exposure per unit surface area. As we have already seen, the court form with a low solar exposure performed badly because it had a low surface area as well. Its solar exposure per unit surface area was the highest.

One could therefore begin with a form with a large surface area and see if it is possible to limit its solar exposure by re-arranging it, by changing its orientation and by decreasing the distance between buildings. A more fruitful and easier approach, however, is to choose a built form with low solar exposure and to try to increase its surface area. This is achieved easily by surface articulation and by perforations in the building mass.

This in fact the method used in Jaisaliner, a medieval town in the Thar Desert in India. The overall built form of Jaisalmer has many shared walls and therefore rather low solar exposure (Figure 7). The building mass is broken up by courtyards and the overall building surface has many projections in the form of balconies and sunshades. But what is really remarkable is the articulation of the building surface itself. The entire stone facade of the Jaisalmer house is intricately carved, creating small fins which increase the surface area many times (Figure 8). It is not a mere coincidence that the thermal performance of these buildings is remarkably good (Gupta, 1985).

Conclusion

It has been demonstrated that solar exposure by itself is not a good index of the efficiency of a building form in a hot climate and that other building features can nullify the effect of solar exposure. In view of the fact that massive building elements such as brick walls and concrete roofs moderate solar heat gains even in cold climates, the applicability of solar exposure as a measure of building efficiency is doubtful even here. However, if one could have two building forms equal or nearly equal in all respects except for solar exposure, the choice between them could be based upon solar exposure.

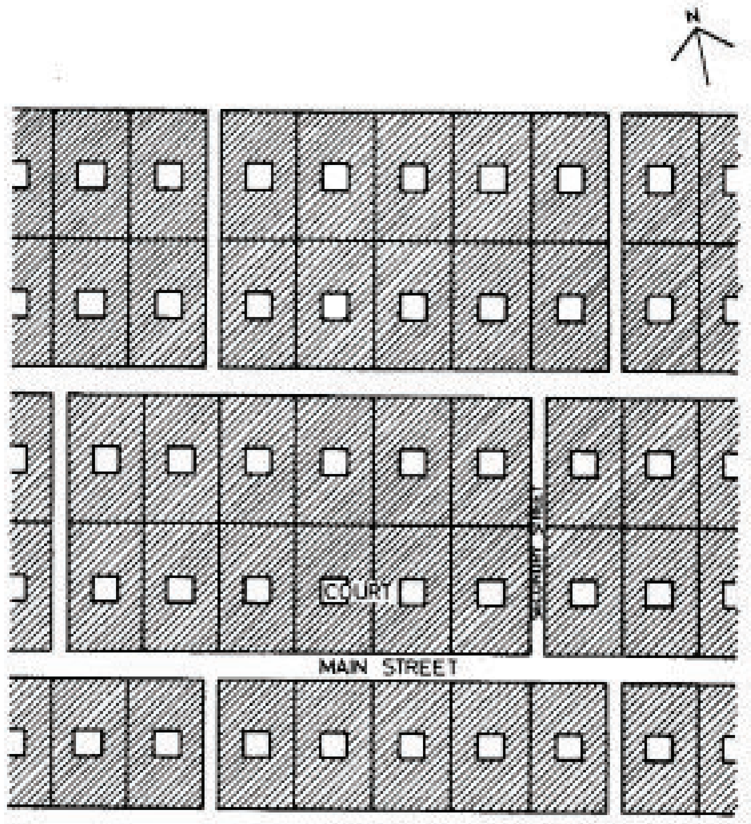

Figure 7. Schematic plan of Jaisalmer town

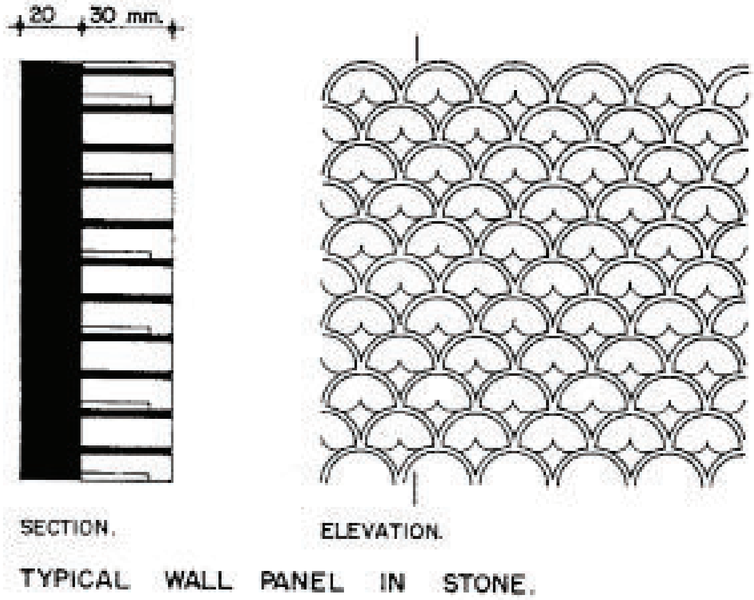

Figure 8. Detail of building facade of a Jaisalmer house

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