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MIRROR BOOSTERS FOR SOLAR COOKERS—II

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Abstract—The effect of elongation (ratio of length/width of aperture) of rectangular apertures, provided with one single booster mirror (hinged on the northern edge of the aperture), on the energy collection pattern is investigated in this study. The system is kept in a fixed position to collect the maximum energy at noon. This is the case with many solar appliances. It is found that the elongation has a significant bearing on the total energy collection. Rectangular apertures with mirror boosters have higher specific energy collection when compared with similarly boosted square apertures; specific energy collection being defined as energy collection per unit area in a given interval of time. The maximum effective elongation is found to be around 3 under conditions prevailing at Warangal. Only the beam component of solar radiation is considered.

Box type cooker   Rectangular aperture   Mirror booster   Horizontal aperture   Fixed orientation   Elongation

NOMENCLATURE

A_a = Area of aperture (m^2)
A_e = Effective area of aperture illuminated by mirror (m^2)
CF = Concentration factor
E_I = Direct energy flux incident on aperture (W/m^2)
E_R = Reflected energy flux incident on aperture (W/m^2)
E_T = Total energy flux incident on aperture (W/m^2)
G = Intensity of solar radiation (W/m^2)
G_{sc} = Solar constant (W/m^2)

Greek letters

α = Altitude
β = Mirror angle
γ = Azimuth
δ = Declination
ϕ = Latitude
ω = Hour angle
ψ = Angle between mirror normal and incident ray

Subscripts

b = Beam component
m = Mirror
n = Normal surface
o = Horizontal surface
r = Reflected ray
s = Sun

INTRODUCTION

In India, box type cookers have been built in varying sizes. The aperture area of these cookers varies from 0.1 m^2 to several m^2. The cookers with areas up to 0.25 m^2 have a square aperture. They are known as family size cookers and are meant for use by a single family.

Several institutions have tried larger size cookers, known as community cookers. The feasibility of such cookers has been demonstrated by the Tamil Nadu Agricultural University of Coimbatore.

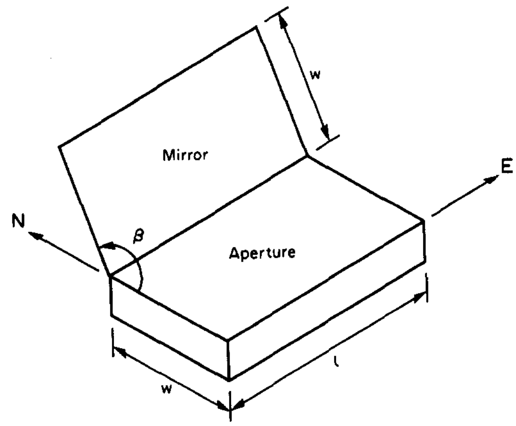

Fig. 1. Orientation of cooker and mirror.

The larger size cookers have, however, not been popular because community cooking is rarely used. Organizations like police, military, etc., do have such a need, but they are not yet attracted by solar cooking. Another solar device which has a horizontal aperture is the solar still. In this case, the glass cover is not to be considered as an aperture, as it does not control the ingress of radiation. Boosters have not been used with solar stills, so far, though there is no reason which precludes their use. This study is applicable to the case of solar stills, as well as passive cookers, in equal measure.

Intuitively, the rectangular aperture with the longer side kept along the prime meridian has been used for these designs. The width (along the meridian) has rarely exceeded 0.75 m. In this article, an investigation into the comparative performance of rectangular apertures with boosters has been made. With other factors being common, specific energy collection ratios of rectangular apertures are compared with square apertures. The aperture, in all cases, is assumed to be horizontal. The declination is assumed to be constant within a day.

Several investigators [1–5] have studied the effect of booster mirrors on solar cookers. Meinel and Meinel [6] have presented different types of mirror booster systems demonstrated by several investigators. Narasimha Rao *et al.* [5] have made an analysis of the energy accretion pattern in a box type solar cooker with a single adjustable booster mirror hinged on the northern edge of the cooker in three different modes of azimuthal adjustment.

METHOD OF ORIENTATION

In the present investigation, a horizontal aperture in fixed orientation, for collection of maximum energy at noon, is chosen. A mirror of the same width as that of the aperture is hinged on the northern edge of the aperture. The mirror is kept fixed at the optimum angle to reflect all the incident radiation on to the aperture at solar noon. The length of the aperture, which is equal to that of the mirror, is varied. The orientation of the cooker and booster mirror is shown in Fig. 1.

METHOD OF COMPUTATION

The variation of declination within a day is ignored in the present computation, thereby validating the symmetry of radiation during the day about solar noon. Only the beam component of insolation is considered.

The altitude and azimuth of the sun for a given declination and hour angle are found by solving the spherical triangle [8] for only Warangal City ($\phi = 18°$). The optimum mirror angle to reflect all the rays on to the cooker aperture at solar noon can be obtained using the equation [1]

$$\beta = 60 + \tfrac{2}{3}\alpha_s. \quad (1)$$

An orthogonal coordinate system is chosen with the XY plane horizontal and the XZ plane located on the meridian treated as the primary coordinate system and is designated by XYZ. The

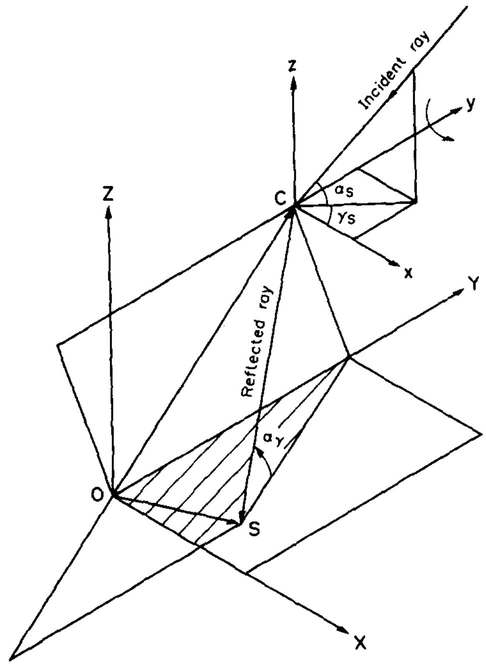

Fig. 2. Coordinate systems.

incident ray is considered as a unit vector having the same azimuth and altitude as the sun. The XYZ coordinate system is shown in Fig. 2.

A secondary coordinate system with origin at "C" (the top right-hand corner of the mirror) is obtained as follows. The primary system is parallel transposed to "C" and is rotated by $(90 - \beta)$ about the y-axis in a direction shown in Fig. 3, so that the XY plane is now coincident with the plane of the mirror. Using an appropriate transformation, the components of the unit vector in this coordinate system are computed. Using the laws of planar reflection, the components of the unit vector of the reflected ray are found. When the vector representing the reflected ray intersects the aperture plane, its Z coordinate in the primary coordinate system is zero. This condition is used to compute the image of "C" in the XY plane. When a straight line parallel to a plane, is projected on to the plane to form an image, the line and its image are parallel. By use of this projectivity property, image coordinates of other corners of the mirror on the XY plane are determined. These, together with the coordinates of the corners of the aperture enable the proportion of reflected beam passing through the aperture to be computed. The altitude of the reflected ray, α_r, is found by determining the vector representing the reflected ray in the XYZ coordinate system. Considering

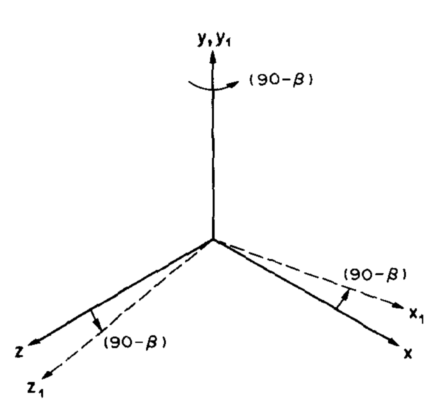

Fig. 3. Rotated XYZ coordinate system.

Hottel's model of atmospheric transmittance [9] for the beam radiation incident on a surface normal to the sun's radiation, at Warangal (lat = 18°N, long = 79.5°E and altitude = 275 m above mean sea level) the beam radiation is

$$G_{bn} = G_{sc}\left\{0.14648 + 0.72425 \exp\left[\frac{-0.36855}{\sin(\alpha_s)}\right]\right\}. \quad (2)$$

The intensity of the beam radiation on a horizontal surface is

$$G_{bo} = G_{bn} \times \sin \alpha_s. \quad (3)$$

The average values of transmittance of the glass cover of the aperture and the reflectivity of the mirror are chosen as 0.85 within the range of the sun's altitude for $\omega = 0$–$60°$. The energy collection of the aperture area due to the beam component incident directly on the aperture is given by

$$E_I = G_{bn} \times A_a \times 0.85 \times \sin(\alpha_s). \quad (4)$$

The energy reflected by the mirror on to the aperture is given by

$$E_R = G_{bn} \times \sin(\alpha_s) \times \sin(\alpha_r) \times A_e \times 0.85 \times 0.85 \times \cos(\psi). \quad (5)$$

The total energy received by the aperture is given by

$$E_T = E_I + E_R \quad (6)$$

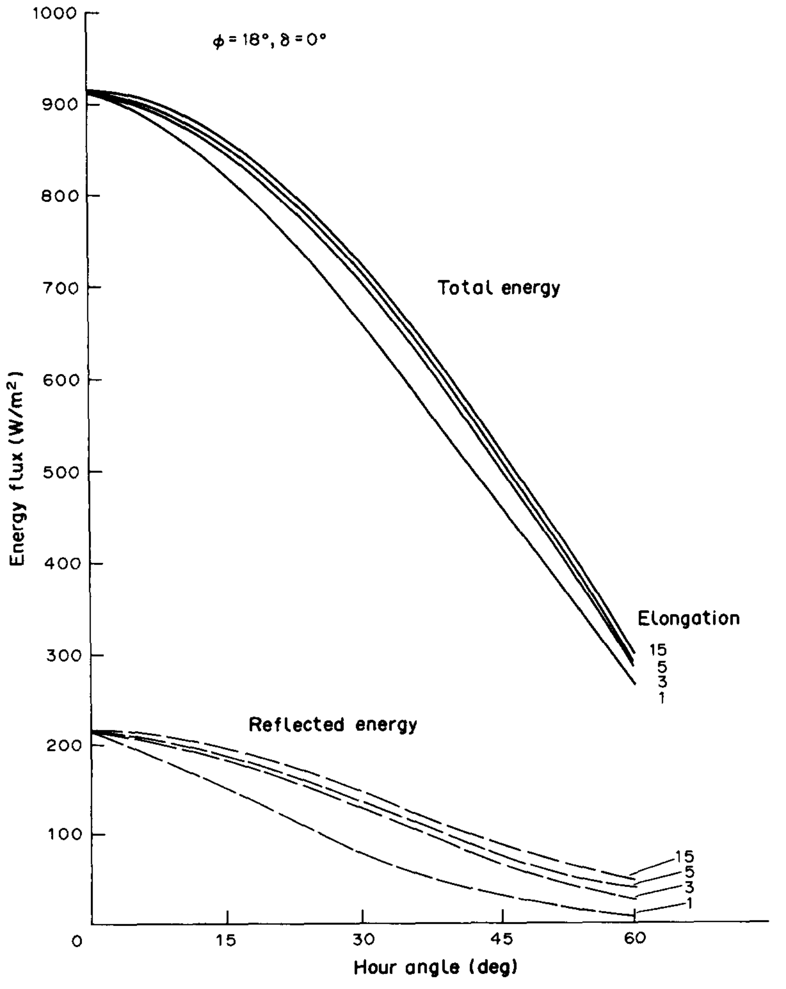

Fig. 4. Total energy flux incident on the aperture vs hour angle.

The concentration factor is given by

$$CF = \frac{E_T}{E_I}. \tag{7}$$

These calculations are carried out for Warangal for five specific days of solar declination of −23.5, −10, 0, +10 and +23.5° for various aperture elongations.

RESULTS AND DISCUSSION

The instantaneous values of energy collection per m^2 of the aperture vs hour angle for different elongations (ratio of length to width of an aperture) are shown in Fig. 4 for Warangal for a declination of 0°. This graph shows that there is a marked increase in the instantaneous values of energy collection as the aperture elongation increases from 1 to 3. Incremental values of energy collected show a positive and declining tendency with further increases in elongation. Beyond the value of 3 of elongation, the incremental ratio of energy collection is <0.01 and ceases to be of any significance. The same trend is noticed on other days of solar declination −23.5, −10, +10 and +23.5°.

The concentration ratio of energy collection due to the booster mirror vs hour angle for various elongations of the aperture are shown in Fig. 5 for Warangal on a day having 0° declination. The concentration ratio, *CF*, is given as the ratio of the energy collection by the aperture with the booster mirror to the total energy collection by the aperture without the booster mirror. It is clear from this figure that there is a significant increase in the concentration ratio as the aperture elongation increases from 1 to 3. The increase in the concentration ratio is marginal once the aperture elongation ratio reaches seven and above. A similar trend is observed on other days also.

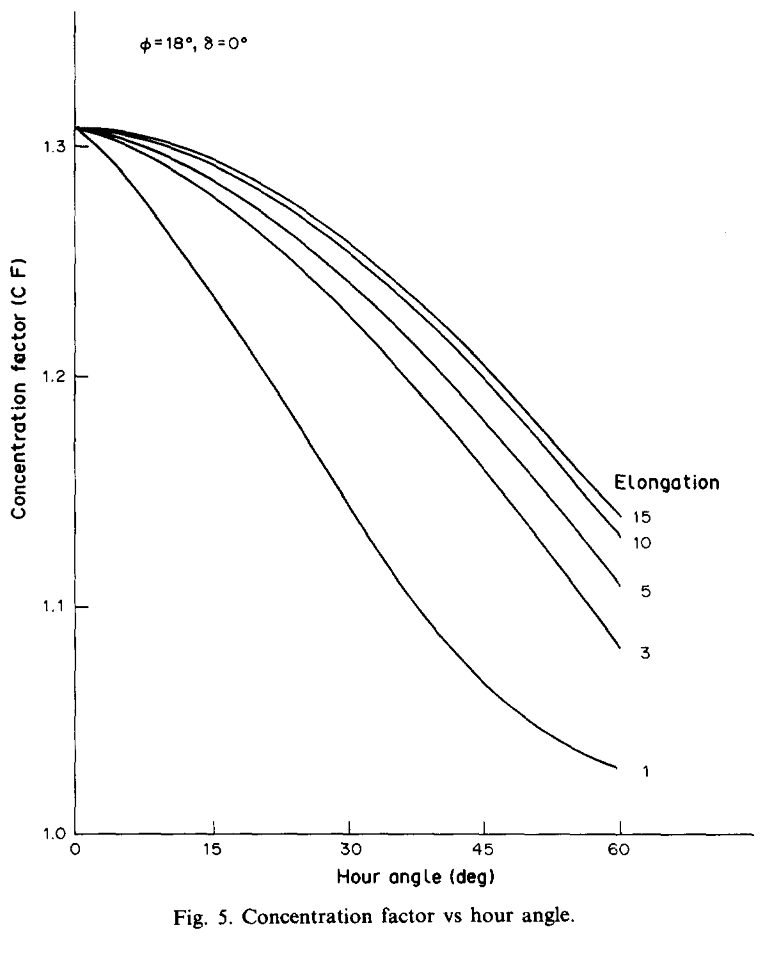

Fig. 5. Concentration factor vs hour angle.

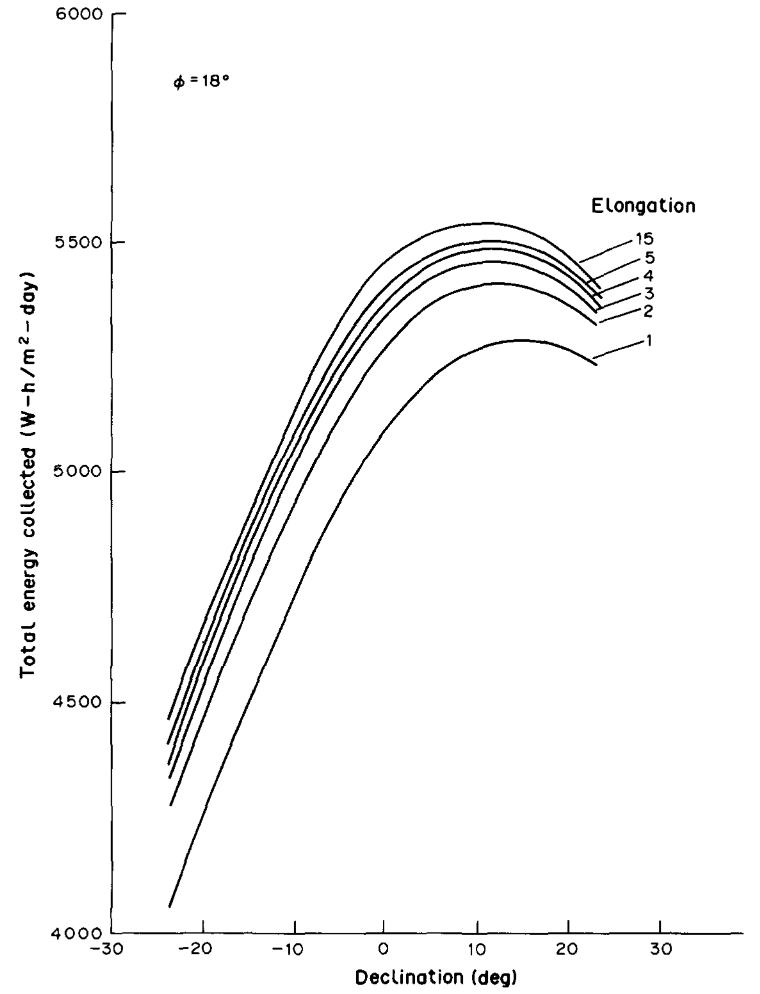

Fig. 6. Total energy collected per day vs declination of the sun.

Figure 6 shows the total energy collection per day vs declination for various apertures as obtained by integrating the areas under the curves, a sample of which is shown in Fig. 4, for $\delta = 0°$. The total energy collection per day increases with increase in declination, reaches a maximum and then drops down on further increase in the declination. The reason for this is that even though the radiation directly incident on the aperture increases with the declination, at higher values of declination this increase is offset by the decrease in the energy reflected from the mirror. The computed values for elongation of unity are given in Table 1.

Figure 7 is a cross plot of the values taken from Fig. 6. The effect of increase in elongation on total energy collected per day is clearly seen in this figure. Elongations beyond 3 do not seem to

Table 1. Solar radiation flux at noon on different days (elongation = 1.0)

				Energy flux collected by the aperture at noon		
Sl. No.	Declination (°)	Altitude of the sun at noon (°)	Mirror angle (°)	Directly incident (W/m^2)	Reflected from the mirror (W/m^2)	Total energy flux collected by the aperture (W/m^2)
1	23.45	48.5	92.4	507	275	782
2	−10.0	62.0	101.4	631	244	875
3	0.0	72.0	108.0	695	215	910
4	+10.0	82.0	114.7	733	183	916
5	+23.5	95.5	123.7	737	140	878

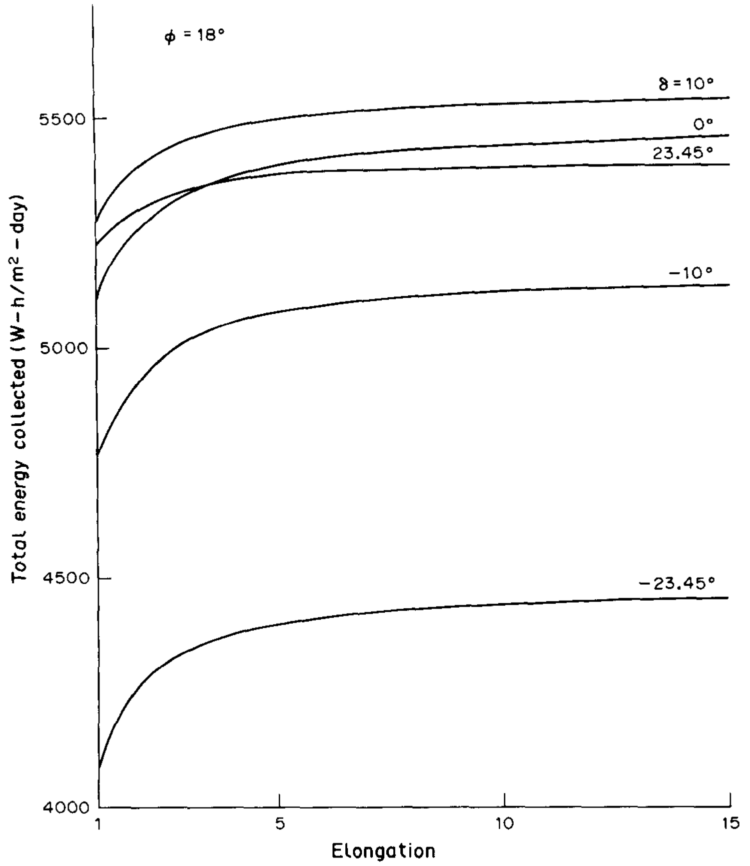

Fig. 7. Total energy collected per day vs aperture elongation.

contribute to significant increase in the energy collection, as mentioned earlier; 3 seems to be an optimum value of elongation for all days in the year.

CONCLUSIONS

The following conclusions are drawn from the results obtained in this investigation:

(1) In the case of horizontal apertures, rectangular apertures ($1 < \text{elongation} < 3$) are more efficient than an equal area of square apertures when the total energy collected in a day is the criterion.

(2) The efficiency of day long energy collection increases with elongation. However, the second differences of the increments are negative. The efficiency is almost a constant for values of elongation >3.

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