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STRIP ELEMENT MIRROR BOOSTERS FOR SOLAR DEVICES

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Abstract—The requirement of large mirrors for enhancing the energy collection of large solar devices has several problems. A strategy that one should proceed to solve the problems of low levels of concentration before tackling those of high levels is propounded. In this paper, two types of strip element mirror boosters, which overcome these problems are described. The systems mentioned herein are suitable for providing precisely fine tuned solutions to problems where low level concentration is of importance. The geometry, construction, application and relative advantages of both additive and multiplying systems are mentioned in this paper. These booster systems can be used to provide low level concentration to many solar devices such as photovoltaic arrays, water heaters, etc. The mirror systems described in this paper are fully tracked ones.

Mirror elements   Additive system   Multiplying system   Low level concentration
Mirror stacks   Receiver shape

NOMENCLATURE

A = Area
C = Concentration ratio
E = Energy
I = Intensity of solar radiation
l = Length

Greek letters

α = Altitude of the sun
β = Mirror angle
ρ = Reflectivity of the mirror
ψ = The angle between the incident ray and the mirror normal

Subscripts

a = Area concentration ratio
b = Beam component of insolation
e = Energy concentration ratio
i = Incident radiation
r = Reflected radiation or the receiver
s = The sun
m = Mirror

INTRODUCTION

Solar concentrators have been known to have a great potential ever since Archimedes proposed them [1]. They held an enduring fascination due to the high energy flux they generate. However, their application in engineering practice has not been commensurate with their potential.

For sometime now it has become evident that very high flux systems, though spectacular, are somewhat further away in time. A more pragmatic approach to usher in high energy flux technology would be through smaller steps. Smaller concentration ratios will provide the required experience and the skills necessary for building devices of higher concentration.

It is interesting to note that medium and high concentration devices attracted maximum attention due to their spectacular nature while not much attention has been paid to low concentration devices.

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Plane mirrors provide concentration of energy flux by reflecting additional energy onto receivers. Since mirrors are cheaper than various solar devices they enhance the economic viability of solar devices like photovoltaic arrays, etc. The sizes of the mirrors to be used in such cases will be comparable to the sizes of the devices themselves. Use of such large mirrors poses several problems. Thus, there is now a need to develop a Fresnel equivalent in catadioptric systems to avoid these problems. A few such systems are described here. All these systems are designed for complete tracking, i.e. the sun rays are always perpendicular to the receiver surface.

The concentration ratio in these devices is below 5x and could be as low as 1.1x. The philosophy of these devices is to take advantage of marginal possibilities for performance improvement as and when they occur. For example on cold days when ambient temperature is $< 10°C$ it may be possible to overload a solar cell by about 20% (concentration ratio = 1.2x) without raising its surface temperature beyond the operational range. Similar exercises could be attempted when insolation levels are low during periods of larger hour angle. Such fine tuning could be attractive where an operator is available to attend a cluster of devices. Usually, engaging an operator is a far cheaper process in the developing countries than using servocontrolled devices.

CLASSIFICATION OF LOW LEVEL CONCENTRATION DEVICES

Low level concentration devices could be further subdivided into two groups. They are named as additive and multiplying devices. An element like a mirror or a lens could be used to increase the flux impinging on a device, irrespective of its position in space, it is known as an additive system.

A good example of an additive system is a plane mirror shown in Fig. 1. Consider a mirror element M_1, shown in Fig. 2, placed between the parallel lines *ab* and *cd*. It is evident that if the mirror is displaced parallel to itself to any position between these parallel lines, it would contribute the same amount of additional energy flux to the devices. A little reflection will make it evident that several such mirrors could be placed at different positions and/or orientations. Also mirrors M_1–M_6 in Fig. 2 would constitute a Fresnel equivalent in a catadioptric system.

Consider the conical mirror elements shown in Fig. 3. The well known conical concentrators can be considered as a unit composed of several of these elements. In Fig. 4, a new method of utilization of these elements is suggested. Instead of a cylindrical receiver placed on the axis of symmetry, as in the case of "Axicon" [1], a flat circular receiver is placed normal to the axis

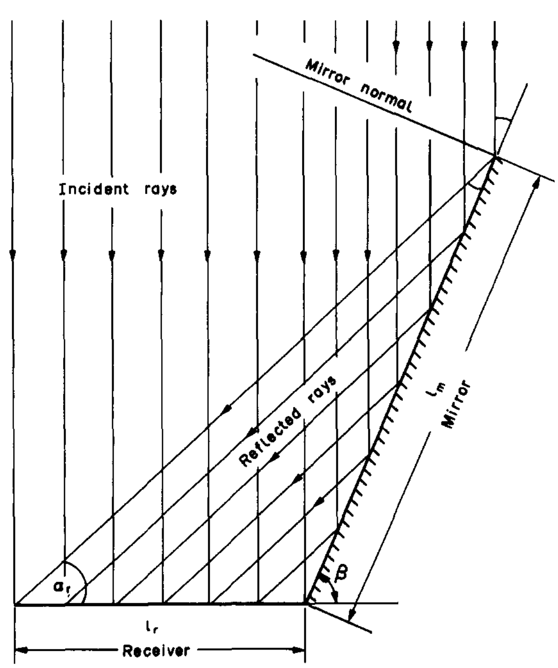

Fig. 1. Plane booster mirror.

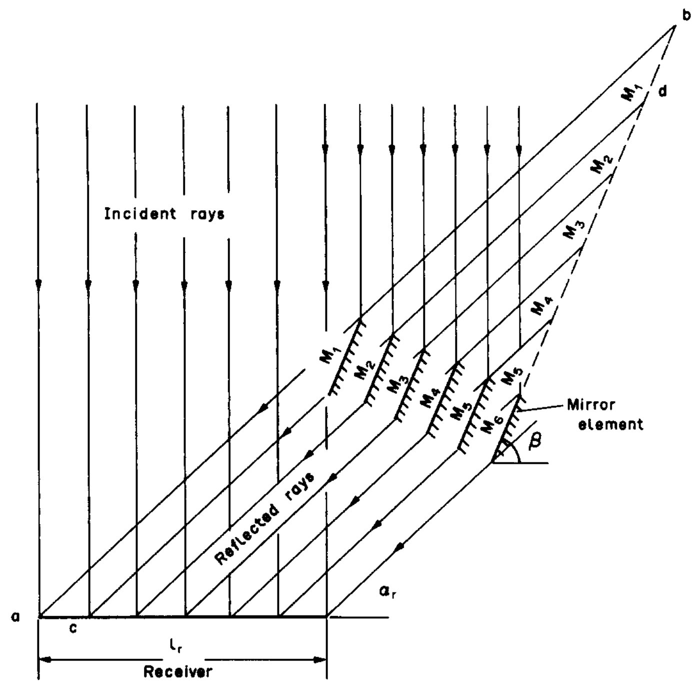

Fig. 2. Staggered strip element mirror array.

of symmetry. With this modification, it becomes possible to use several such elements of different cone angles. In this case, the concentration ratio is uniform over the entire receiver area, unlike in the case of "Axicon" [1]. Further, in this new arrangement, a much wider range of concentration ratios are possible. It is well known that the area concentration ratio is the ratio of the area of the beam intercepted by the reflector and receiver to that of the receiver. If the dimensions of the reflector shown in Fig. 3 are increased in a constant proportion, then the reflector would need to be displaced upwards in the same proportion. The surface area of the reflector and the area of the solar beam intercepted by it would increase as the square of the proportion (the receiver size remaining constant throughout). Such a system, where the concentration ratio is changed non-linearly is known as a multiplying system.

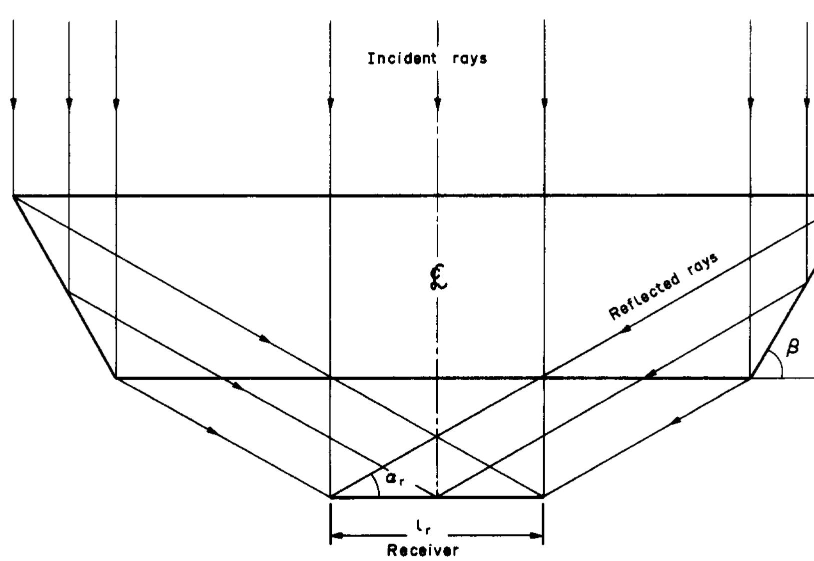

Fig. 3. Conical mirror element.

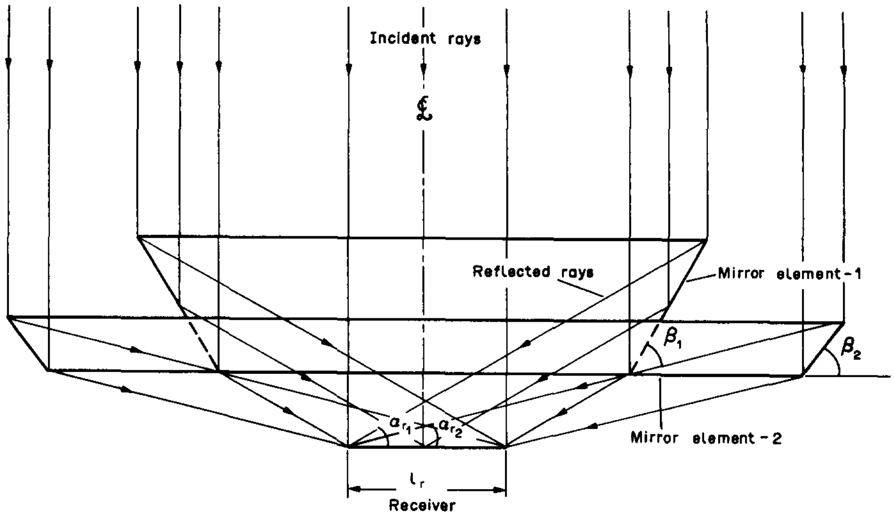

Fig. 4. Multiple conical mirror elements.

GEOMETRY OF THE DEVICES

Additive systems provide a considerable amount of flexibility to the designer. The chief factors which provide flexibility are:

(i) angles of incidence and reflection,
(ii) ratio of sizes of interception area and receiver area, and
(iii) the shape of the receiver.

The best angle of the mirror is one at which the reflected beam illuminates the entire surface of the receiver. This condition fixes the orientation and relative size of the mirror simultaneously. It is possible to have several mirrors or stacks having different orientations and they can be used simultaneously. This scheme is illustrated in Fig. 5. The stack of mirrors M_1–M_6 serve the same purpose as the single mirror shown in Fig. 1. They would also be treated as a single additive unit.

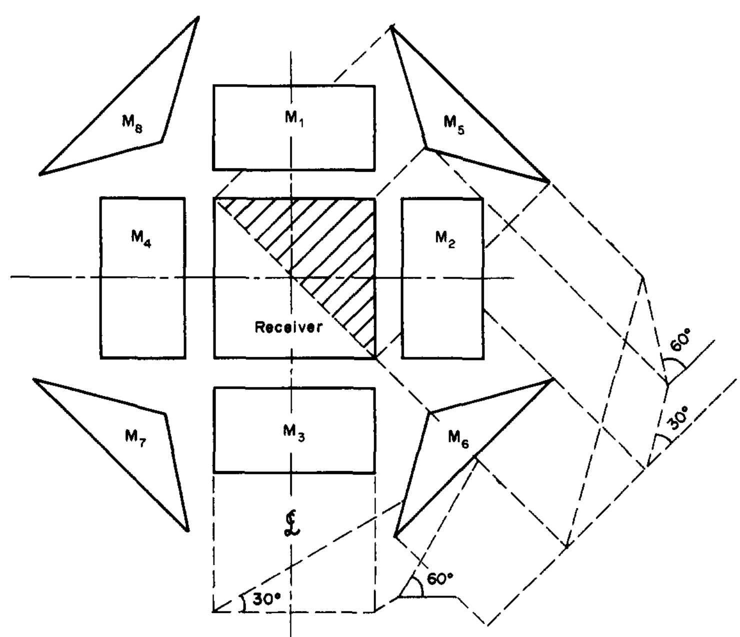

Fig. 5. Multiple plane mirror boosters.

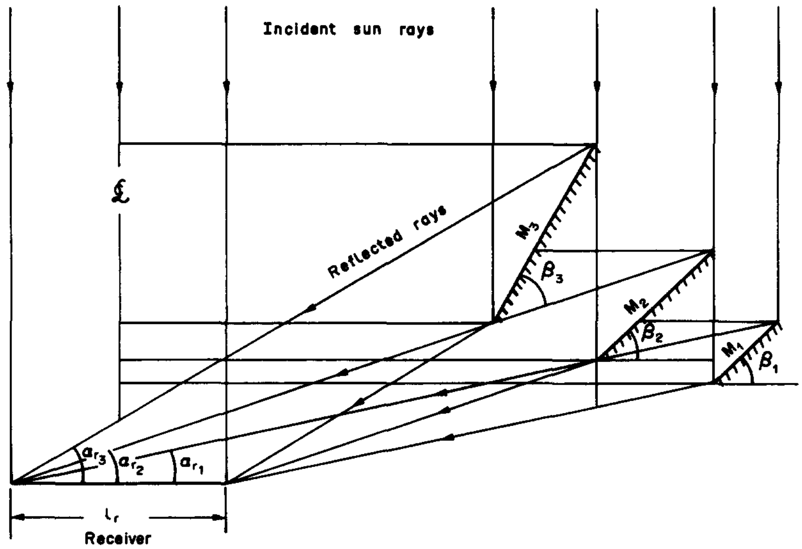

Fig. 6. Geometry of conical mirror elements.

In Fig. 5 the number of stacks and their characteristics will be determined by the ratio of the beam area intercepted by the mirror system to the area of the receiver. Once the mirror angle is chosen for one element, the geometry of the other elements can be obtained either graphically or by simple computation.

The shape of the receiver also provides considerable flexibility to the system designer. This concept is explained by an example illustrated in Fig. 5. Mirror stacks M_1, M_2, M_3 and M_4 each fully illuminate the entire receiver area. Further, the triangular mirror stacks M_5, M_6, M_7 and M_8 reflect radiation on to different halves of the receiver. For example, as shown in Fig. 5, the mirror stack M_5 illuminates the shaded area of the receiver. Triangular stacks are used to take advantage of the triangular gaps available at the corners.

The choice of the receiver shapes and disposition of the mirror stacks is limited only by the imagination of the designer. One can try and sketch a variety of arrangements for each of the receiver shapes, such as hexagons, octagons, circles etc.

The arrangement of two conical mirror elements is shown in Fig. 4. Several such mirror elements can be arranged to provide additional energy as illustrated in Fig. 6. The effectiveness of the conical mirror element decreases as it moves away from shallow angles.

CONCENTRATION RATIO

The energy concentration ratio in both the additive and multiplying systems is given by the following equation

$$C_e = 1 + E_r/E_i \tag{1}$$

where

$$E_r = I_b A_m \rho \cos\psi \sin\alpha_r \tag{2}$$

and

$$E_i = I_b A_r \sin\alpha_s \tag{3}$$

therefore

$$C_e = 1 + (A_m \rho \cos\psi \sin\alpha_r / A_r \sin\alpha_s). \tag{4}$$

The area concentration ratio is given by the following equation

$$C_a = 1 + (A_m/A_r). \tag{5}$$

In the case of the additive systems, the area concentration ratio will be the ratio of the sum of the areas of the receiver and the individual mirror elements to the receiver area. The total energy reaching the receiver can be obtained by summation. It is important to note that the receiver is uniformly illuminated by each single mirror. In the case of mirrors illuminating half the area of the receiver located on diagonals (see Fig. 5), a pair of such mirrors are to be considered as a unit for computation. If the concentration ratio is to be varied, then a unit which illuminates the whole area of the receiver must be either cut-in or cut-out of the system. Unless the entire receiver is illuminated there will be problems of differential heating and consequent damage to equipment.

The concentration ratio could be determined on the basis of one or many of the following criteria:

(a) The safe tolerable system loading. This is usually determined by the need to dissipate waste heat and the capacity to do so.

(b) In thermal devices, it is determined by the requirement of achieving a given stagnation temperature.

(c) Radiation intensity and ambient condition. As one moves towards polar regions, the intensity of incident radiation falls, while the capacity for cooling increases due to low ambient temperatures.

(d) Ability of equipment or components to withstand the thermal shock.

In the case of multiplying systems, the basis of computation of concentration ratio would be the same. The area concentration ratio varies in the same proportion as the square of the radius of the conical element. These systems are slightly less flexible and concentration ratio could not be varied easily as in the case of plane mirrors. The only way of varying concentration ratio would be to cut-in or cut-out a complete ring of reflector when more than one ring is present. In the case of these systems, when the upper limit of concentration is reached, the overheating occurs for the following reason. If the sun were a point source of energy, each element of the ring would generate a wedge shaped image on the receiver with the apex of the wedge located at the centre of the receiver. Since the sun is an extended source it is evident that the concentration ratio close to the centre will be higher than those at increasing radial distances. The variation would cause severe differential heating which sets the upper limit of concentration ratio for the system.

In multiplying systems, if the radius of the conical reflector only is varied (keeping receiver area constant), the collection area of reflection also varies. The variation arises due to change in the area of the mirror. Due to this change of scale the other terms are not affected. Here the designer has a powerful method of adjusting the system to various applications.

Efficiency of concentrators could be based on several criteria. For example, it could be based on utilization of area on a given cross-section normal to the beam. The enveloping figure represents the total solar energy available for interception; of this energy, only a fraction is intercepted by mirrors and the receiver. By adopting various layouts, it is possible to vary the ratio of the area intercepted. However, this ratio will always be <1.0. Looked at in this light, the mirror strip systems are slightly less effective than monolithic concentrators. Low efficiency of utilization of area would not be a drawback when sufficient space is available. Only in urban situations could it be a critical criterion. On balance of judgment, the other advantages of strip systems outweigh the area utilization criteria.

ADVANTAGES OF MIRROR ELEMENT SYSTEMS

(1) The engineering systems designer is provided with far greater freedom in layout of components.

(2) Air circulation around photovoltaic cells is greatly improved and therefore better cooling is obtained.

(3) Wind loads are reduced significantly. This also reduces the structural weight of systems.

(4) When several arrays are provided it is a simple job to mask any of them and therefore concentration ratios could be varied at will. For example, it could be reduced during the noon hours of maximum insolation and increased during periods of lower insolation due to lower solar altitudes.

(5) These systems could be designed to accept fairly large orientation errors to make the tracking systems less critical in design and operation.

(6) Concentration devices need to track the sun and therefore have to be rotated. If a large mirror is replaced by a stack of strips/elements, the moment of inertia is reduced significantly. Therefore less torque and power are required for tracking.

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