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Practical aspects of Piecewise-Focusing (PWF) collector design

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Introduction and aims

Fundamental ideas and optical principles underlying PWF collectors for CST power and process heat have been described previously [1,2], and it was shown that PWF collectors have considerably higher thermal output than central receiver systems, per m^2 of reflector surface [3,4]. Other advantages include modularity and simplicity of operation. Only a few of the many possible design variables have been analyzed so far, e.g. the overall slope of the collector face [4], and the number (i.e. relative size) of reflectors that tesselate the collector face [2]. However, it has been assumed that the baseframe can be constructed economically when the collector face is approximately paraboloidal and the aperture is circular (Figure 1), and that each reflector can be curved three-dimensionally so that it is perfectly focused on the receiver at a specified sun elevation.

The overall aim of the present work is to learn more about practical aspects of designing and building PWF collectors, demonstrating both flexibility within the general concept and scope for optimization. Specific aims are (1a) to construct a scale model PWF collector incorporating a very straightforward baseframe design with a flat (not paraboloidal) collector face, (1b) to set up and verify a corresponding numerical model; and (2) to investigate (via numerical modelling) whether simpler, spherically curved reflectors provide adequate focusing at all sun elevations. Note that the scale model and corresponding numerical model emulate reflectors with custom 3D curvature.

Baseframe and reflectors

For simplicity, lightness and rigidity, the baseframe consists of three planes forming a triangular prism, constructed from steel roofing battens and purlins (Figure 2). The frontal plane is tilted towards the sun by 45 degrees, and its width (5.8 m) is twice its height (2.9 m), drawing upon the analyses in Ref [4]. The receiver target is 2.9 m perpendicularly above the centre of the frontal plane. The baseframe has four castor wheels, and rotates around a central pivot on a horizontal concrete apron. Eight hexagonal plywood ‘reflectors’ are mounted on their individual tilting axes, four of them near the extreme corners of the frontal plane where sun rays are turned through the largest angles to reach the target — these are the most difficult cases. Previous work used rectangular reflectors [1,2], but the vertices of a hexagon are closer to its centre compared to the corners of a rectangle (or square) of the same area. About 92 hexagons would be needed to cover the complete frontal plane, allowing small gaps between them, which is equivalent to 160 reflectors covering the circular aperture of previous work [1-4].

Flat mirrors are fixed in the middle of each hexagon, and flat secondary mirrors are placed at several vertices of four hexagons, all masked so that the sun is reflected as small spots on the target. Each secondary mirror is set at an adjustable angle to the plywood so that it can emulate the vertex of a 3D-curved full reflector. Rotation of each reflector about its mounting axis is

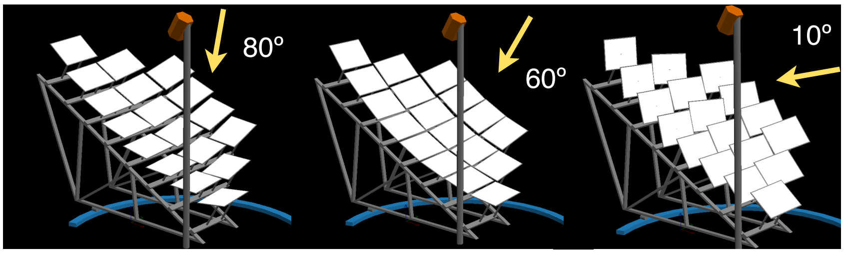

Figure 1. Previous PWF designs [1-4] included an overall paraboloidal shape, circular aperture, and a 30-degree tilt towards the sun. Only the right-hand half of the collector is shown in this simplified CAD model, with three sun elevations indicated.

Figure 2. The model PWF collector. The four ersatz reflectors that have secondary mirrors at several vertices can be seen towards the lower left and upper right in the front view.

controlled by fingertip pressure and friction in the mounting joints, except for the reflector shown in Figure 3. Here the linear actuator that would be used in full-scale practice is emulated by a threaded rod with adjusting nuts. The two reflectors nearest to the middle of the frontal plane were primarily used to verify that the collector was facing the sun squarely during tests — they produce overlapping spots on the centreline of the target (e.g. Figure 4) when the collector is correctly aimed in azimuth and these two reflectors are tilted slightly high in elevation. The numerical model, described in previous work [1,2], rotates a reflector about its mounting axis until the reflected ray from its centre is closest to the centre of the target, and then intersects other rays with the target.

Test results

It has been assumed so far [1,2] that a suitable geometrical concentration ratio at the entrance to a cavity receiver is 2000, in which case all sunlight reflected from the area of the frontal plane must be focused within the circle drawn on the target. For Figures 4, 5(a) and 6(a) all secondary mirrors

Figure 3. A threaded rod controls tilt of this reflector about its mounting axis, as a substitute for a linear actuator.

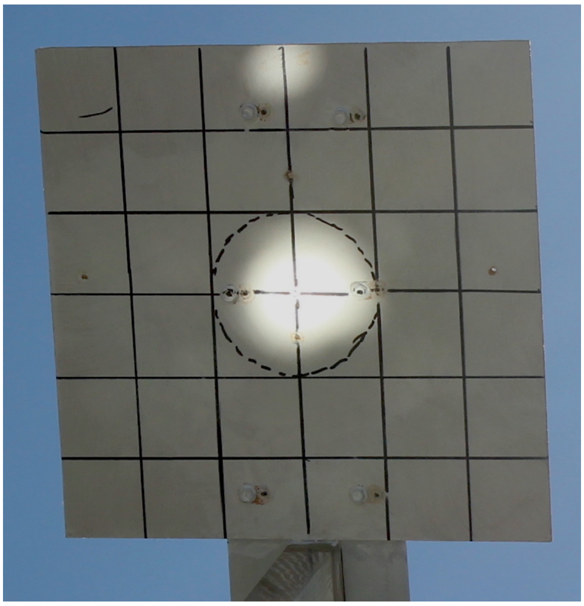

Figure 4. Target. The circle represents the mouth of a cavity receiver with a concentration ratio of 2000. Sun elevation 40 deg.

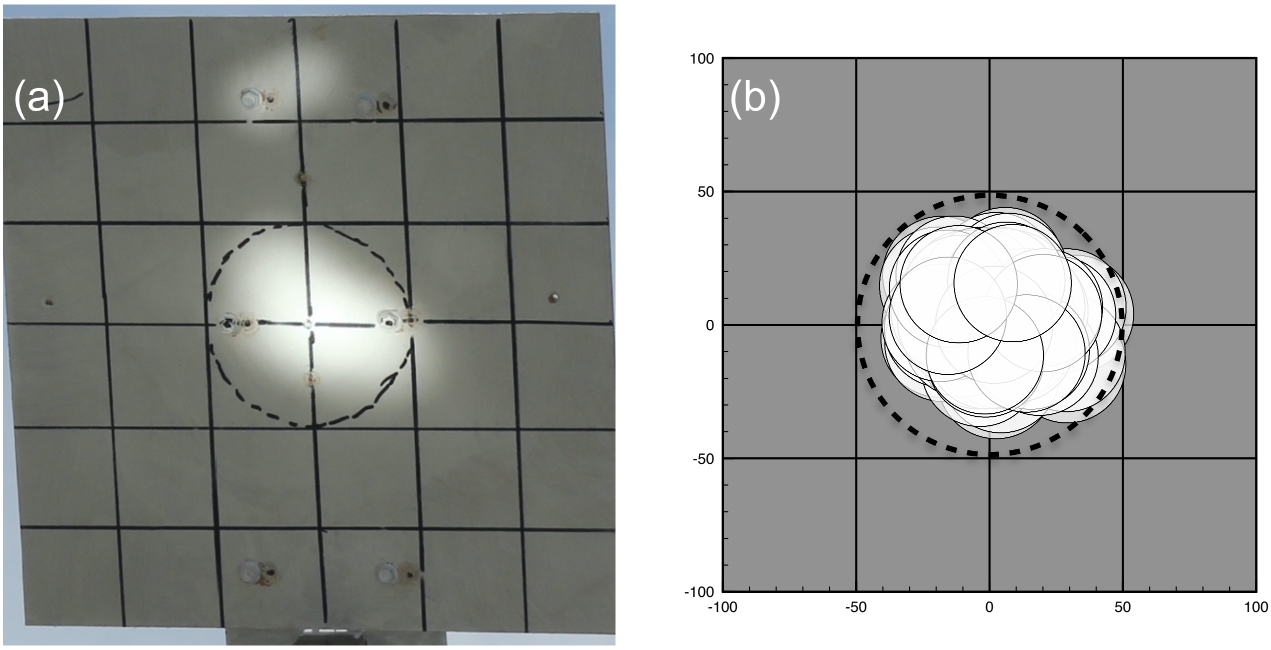

Figure 5. Reflections onto the target, sun elevation 10 degrees. (a) Physical model. (b) Numerical model output under similar conditions.

were adjusted relative to the plywood hexagons so that their reflected spots fell within the target circle when the sun elevation was 38-40 degrees, and no further adjustments were made at the other elevations (10 and 77 degrees). Results from the numerical model, also with perfect aim from the secondary mirrors set at sun elevation 38 degrees, are shown in Figures 5(b) and 6(b). The numerical model includes reflections from secondary mirrors at all six vertices on each hexagon. All other points on each reflector are closer to its centre, and therefore their reflections would be closer to the centre of the target. The finite size of the sun causes blurring of the reflections on the target; ideally these blurred reflections would be ellipses in the computer plots since they approach the target at various angles. The numerical model agrees reasonably well with the physical model (surprisingly well, given measurement uncertainties in construction of the latter), and they show that this simple PWF design works well for a wide range of sun elevations. However the need for

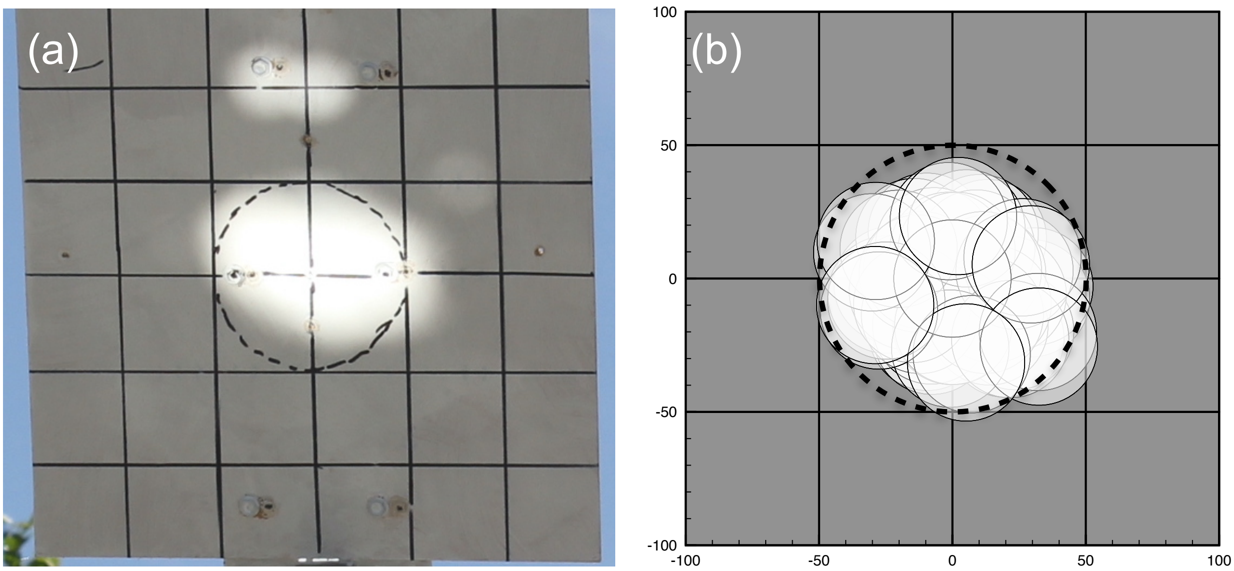

Figure 6. Reflections onto the target. (a) Physical model, sun elevation 77 degrees. (b) Numerical model, sun elevation 75 degrees. The photo in (a) was taken in spring with the whole collector tilted towards the sun by about 12 degrees.

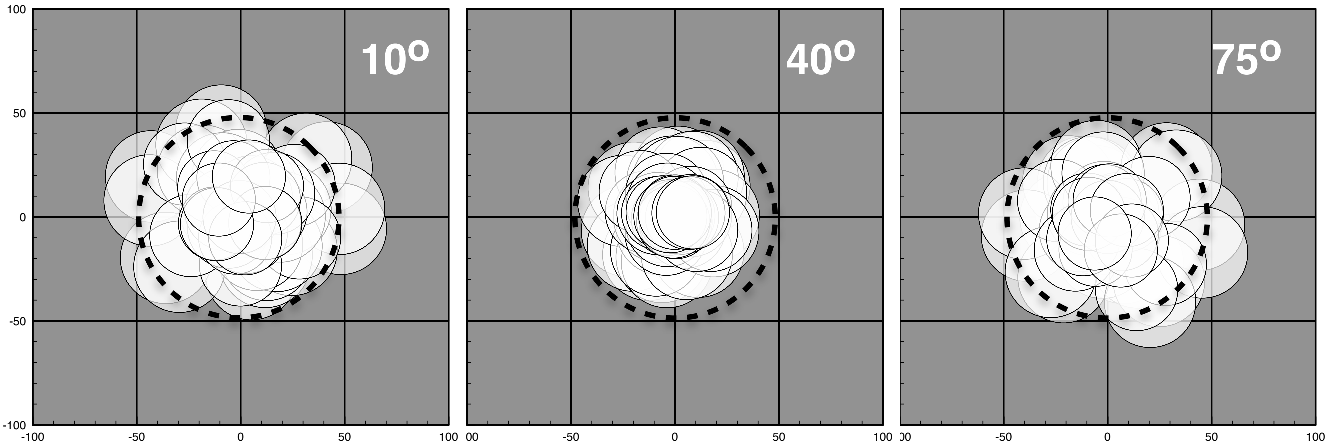

Figure 7. Reflections on the target from spherically-curved reflectors at the noted sun elevations.

custom 3D reflector shapes based on perfect focus at a specified sun elevation implies that each reflector will have a slightly different shape, increasing the cost of production. Spherical curvature, using only a few different radii of curvature across all reflectors, should be more economical.

Tests with spherically-curved reflectors

The numerical model was adapted to utilize hexagonal reflectors in the same positions but with the equivalent of spherical curvature: the mirror-normal at each vertex was angled inwards towards the centre by an equal amount, as would be the case if each hexagon was cut from the surface of a sphere. Results in Figure 7 show that there is degradation of focus quality compared to that of the custom shapes used above, but spillage is only occurring from the extremities of the 'worst-case' reflectors, and satisfactory focus is obtained from almost all the frontal plane area. Three radii of curvature were used for Figure 7, based on each reflector's distance from the target. The change of slope from the centre of a reflector to its vertices was quite small, i.e. 1.8, 2.1, or 2.3 degrees.

Discussion and conclusions

Although the receiver entrance has been shown as circular in the results, a rounded rectangular entrance may be more suitable, following the shape of the frontal plane. The thermal absorber within the receiver could then be shaped as a cylindrical arc, probably a straightforward design.

- The experience of building the model baseframe reinforces previous assertions that a full-scale baseframe will be lightweight, rigid, and economical to construct, if designed for both structural efficiency and good optics. Making width greater than height is beneficial.
- Spherically-curved reflectors with only a few different radii of curvature (instead of many different custom-curved reflectors) will produce satisfactory focus at the entrance to a cavity receiver, simplifying construction and further reducing costs.

Finally, it is worth recalling that a central receiver system of equal thermal output to a PWF system requires of order 1.7 times larger area of reflectors (i.e. heliostats) [3,4]. PWF collectors should be further explored as an alternative solution to the problem of the high cost of a field of heliostats.

References

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