ASIA-PACIFIC SOLAR RESEARCH CONFERENCE

29 Nov - 1 Dec 2022, Newcastle, Australia

Optimization of PWF collectors and comparison to central receiver CST using SAM

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Introduction

The Piecewise-Focusing (PWF) collector was described and analyzed by Bisset [1,2], and the need for optimization in certain aspects of design (especially overall collector tilt) was noted. With the System Advisor Model (SAM) simulation software [3], simulations of Concentrating Solar Thermal (CST) operation may be carried out on an hour-by-hour basis for an entire year, based on Typical Meteorological Year (TMY) weather. SAM is applied here using TMY data at four locations with different latitudes and climates (Table 1). SAM has a 'generic' CST facility, in which the performance of any type of CST collector (e.g. PWF) is modelled by a table of optical efficiencies as functions of solar azimuth and zenith angles, and also includes a detailed model of a 100 MW_e central receiver system. Results here focus on heat added to the heat transfer fluid (HTF) as it passes through the receiver(s), per m^2 of heliostat or reflector, since this is the primary output from solar collectors in CST. Also, since SAM allows detailed control of settings for efficiencies and losses, performance comparisons between PWF collectors and central receiver systems are broken into various stages as sunlight is collected, concentrated, and converted into usable heat.

The SAM central receiver system

Some heliostats in the default 100MW_e central receiver system, with 10 hours of thermal storage and a solar multiple of 2.4, are defocused on clear summer days when the thermal storage reaches full capacity. Since the point of comparison here is the maximum heat collected per m^2 of heliostat (or reflector), the default settings were adjusted until defocusing no longer occurred.

The Piecewise-Focusing collector

Approximately 250 independent reflectors are mounted on a base-frame, forming a roughly paraboloidal surface with its focus at the entrance to a cavity receiver. The entire collector rotates about a vertical axis in order to follow the azimuthal position of the sun, while the reflectors rotate about nearly horizontal axes (at different particular angles to the base-frame) to track the sun's elevation above the horizon [1,2]. The axis of the paraboloidal surface (passing through the cavity receiver) is tilted towards the sun by a (fixed) angle suitable for a given location. This overall angle of tilt controls the values in the table of optical efficiencies that SAM uses for 'generic' CST simulations. The solar multiple in SAM was adjusted to avoid any dumping of excess heat.

Comparison of heat collection performance

Results for heat energy collected in the HTF per year, per m^2 of heliostat or reflector, are shown in Figure 1. Heat output increases with annual DNI as expected, but the PWF output is always greater than that of the central receiver by factors shown as percentages on the figure. These results suggest that PWF power plants are likely to be smaller and cheaper than central receiver systems of equal output, and they may also be economically feasible in regions of moderate DNI, closer to load centres, where central receiver systems are uneconomical.

Optimization of PWF collector tilt and shape

Ideally, the 250 or so reflectors in a PWF collector broadly follow a paraboloidal surface, the axis of which is tilted towards the sun. However, unlike the paraboloidal dish upon which it is loosely modelled, the PWF collector's overall angle of tilt is fixed (Figure 2, left). This permits much more

Table 1. TMY weather data from the National Solar Radiation Database (NSRDB) [4]

Location	Latitude, deg	Annual DNI, kWh/m^2	NSRDB station ID
Daggett, California	34.85	2799	91486
Des Moines, Iowa	41.57	1591	757516
North-Central Mexico	23.29	2789	549592
Northern Chile	−20.99	3387	1399660

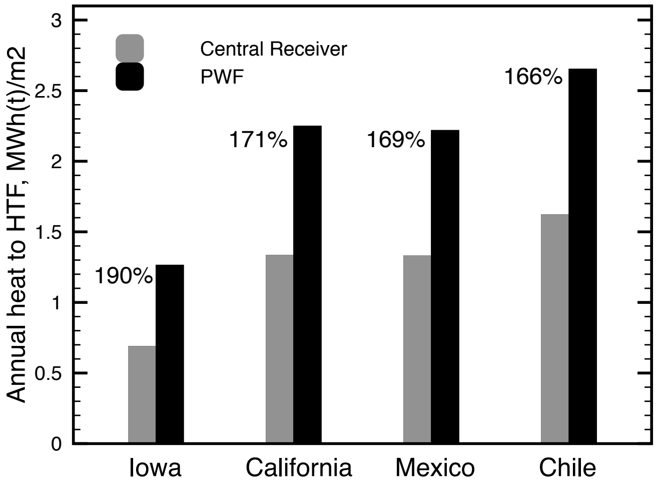

Figure 1. Annual heat collected in the HTF per m^2 of reflector (PWF) or heliostat (central receiver) at four locations.

economical construction and larger sizes than for a dish, while retaining much of the dish's high optical efficiency. Initially the overall collector aperture (Figure 2, right) is assumed to be circular. Simulations were run for all weather locations, and results labelled 'full collector' are in Figure 3. For a circular aperture, increasing tilt rapidly increases the height of the collector's upper rim from the ground, resulting in greater wind loading as well as greater cost of construction. Removing reflectors at the lower part of the rim, so that the overall collector shape is wider relative to its height and reflectors are closer to ground level, improves matters. The collector aperture was divided into five equal sectors, labelled A to E in Figure 2 (right), and the lowest one was deleted. Results for this modified collector, termed '4/5 collector', are compared with the full collector results in Figure 3. Improvements in heat collection using the 4/5 collector are only modest, but they are very worthwhile when the benefits in terms of easier construction are taken into account.

Seasonal variation in performance

Monthly variations for different collector tilts and shapes are examined in Figure 4. Low tilts emphasize summer output, and the 4/5 collector tilted at 50 degrees emphasizes winter output (the effects of a dry winter and late summer rainfall can also be seen in the Mexico results). However,

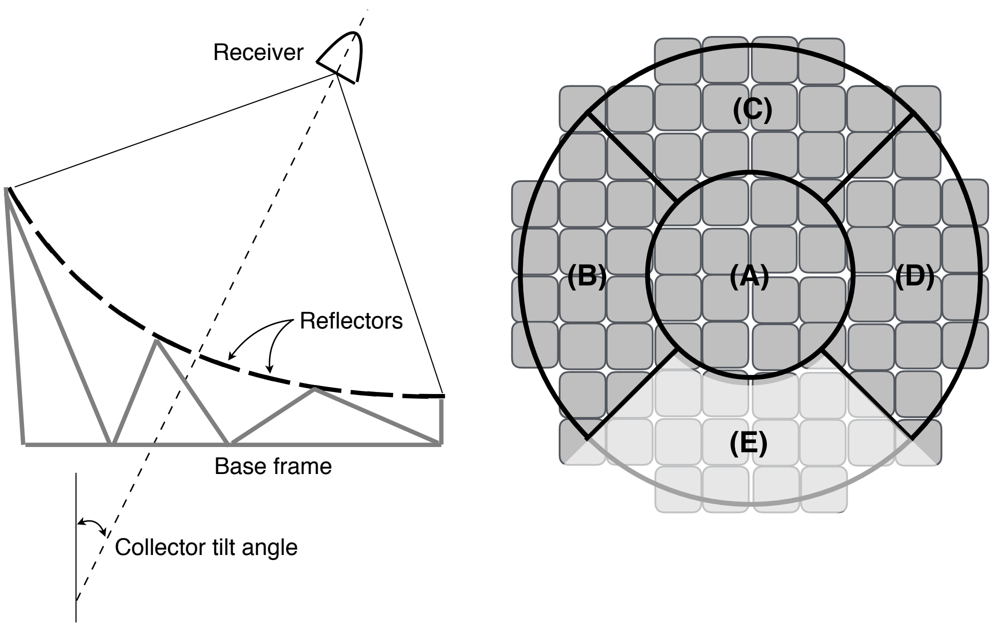

Figure 2. Cross-section side view of PWF collector (left), and view into the aperture from the receiver (right). Sector E is removed for shape optimization.

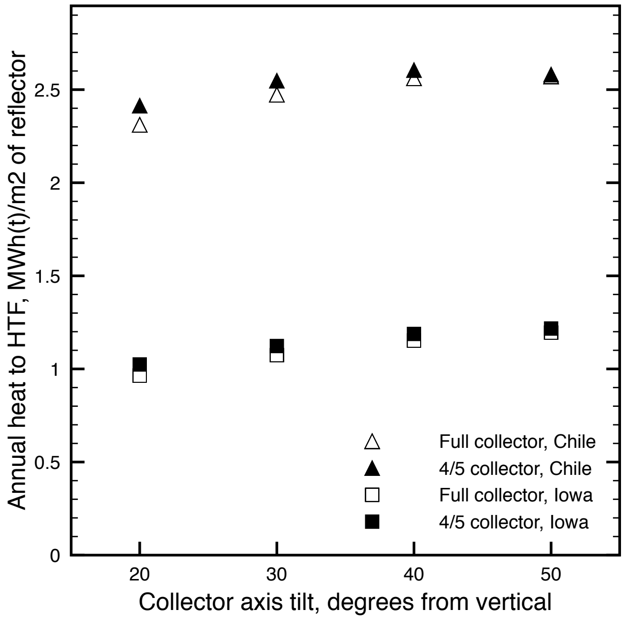

Figure 3. Annual heat collection as a function of overall collector axis tilt for locations at low (Chile) and high (Iowa) latitude. See text for explanations of full and 4/5 collectors.

the highly-tilted collector gives higher output for every month, even in summer. The reason is that the PWF collector's optical efficiency is highest when the sun's zenith angle is more-or-less aligned with collector tilt, which is the case for the 50-degree-tilted collector for several hours after sunrise and several hours before sunset, and the greater output at these times compensates for lower output in the middle of the day in summer. The opportunity to simulate performance from realistic weather data in SAM leads to the somewhat surprising conclusion that a highly-tilted collector works better all year round in a wide range of locations.

Causes of inefficiency and heat loss in PWF collectors and central receiver systems

The maximum rate of heat collection for any CST collector is the product of total reflector area and DNI, and as shown in Figure 1, PWF collectors approach the maximum per m^2 (i.e. the annual DNI from Table 1) much more closely than central receiver systems. The procedure to explore the reasons for this was to turn off all possible losses and inefficiencies in SAM, and then repeat the simulations with the losses/inefficiencies restored step-by-step. Each successive decrease in heat collected represents the effect of each loss or inefficiency. Results are shown in Figure 5. The

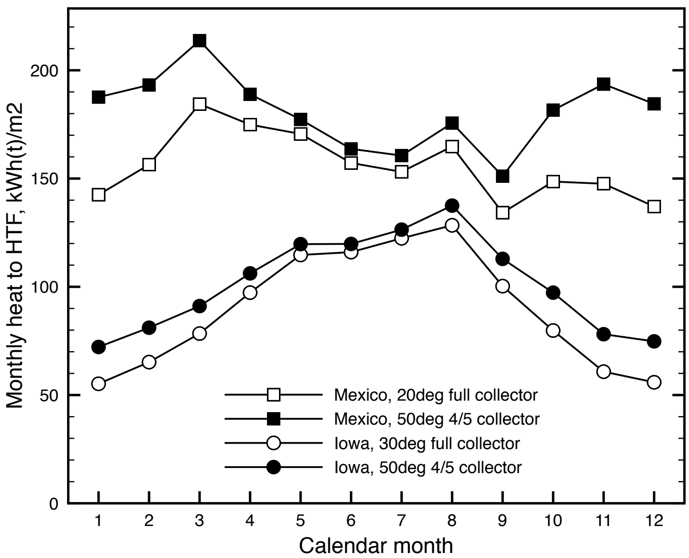

Figure 4. Monthly heat output for different collector tilt angles.

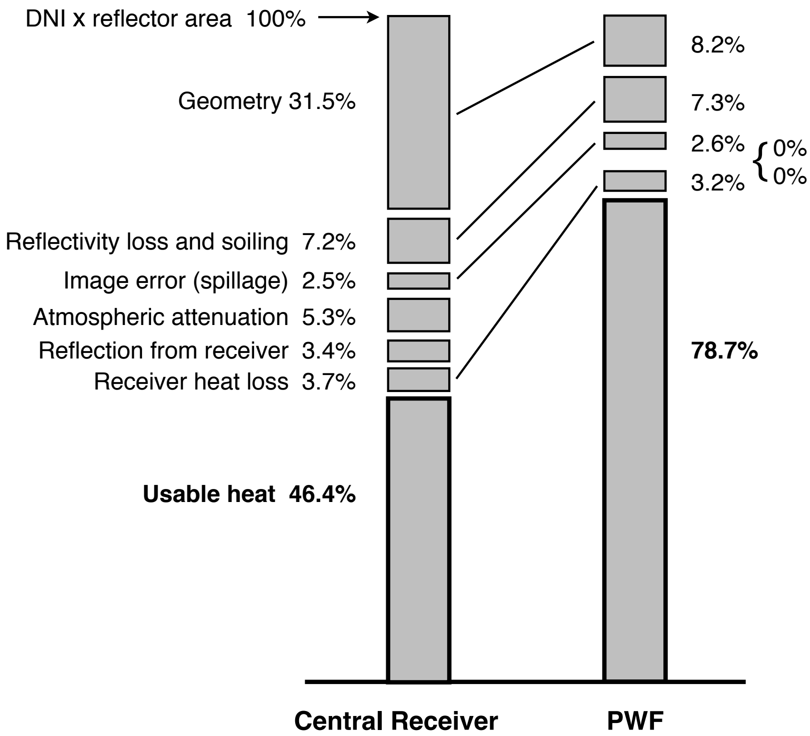

Figure 5. Actual and potential heat collection using the California TMY weather data.

default central receiver system uses a heliostat field that fully surrounds the central receiver tower, and therefore cosine losses are very significant. Shading and blocking are also included within the 'geometry' loss in Figure 5. Reflectors of the PWF collector are always much more 'square-on' to the sun with correspondingly lower cosine losses, and there is minor shading but no blocking. Mirror reflectivity and soiling, reflector/heliostat availability and receiver/tower shadow are similar for the two systems, as is spillage caused by slope error of mirror surfaces.

Atmospheric attenuation is negligible for the relatively compact PWF collectors, but can be quite serious for a central receiver system where some heliostats are nearly 2 km from the receiver. The SAM default values apply for a reasonably clean atmosphere with occasional moderate levels of smog or dust, or equivalent [5], and result in the 5.3% loss shown. Absorptivity of the central receiver is 94%, i.e. 6% of impinging sunlight is reflected, which is 3.4% of maximum sunlight. Absorptivity of the PWF cavity receiver is assumed 100%. Heat loss by convection and re-radiation is fairly similar for the two systems as a percentage of maximum sunlight. Summarising, PWF collectors perform better than central receivers because the latter lose 23.3 more percentage points of potential heat collection through inferior geometry (mainly cosine losses), 5.3 percentage points from atmospheric attenuation, and 3.9 percentage points more at the receiver.

References

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