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Medium temperature solar thermal collector with an internally integrated CPC

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Abstract

Heat is a major component of global energy consumption, producing significant greenhouse gas emissions. Solar thermal systems capable of producing medium-high temperature heat are a viable technology to offset some of the emissions by supplying heat to industrial processes. In this paper, we introduce a novel non-tracking solar collector that employs an internally integrated compound parabolic concentrator. We show that this system can produce thermal output at above 200˚C with a minimum thermal efficiency of 50%.

1. Introduction

About half of global energy consumption is in the form of heat that generates one third of the total CO_2 emission (Eisentraut and Brown 2014). The required temperature for such applications varies from below 100˚C to above 1000˚C. Solar energy hasn't yet been very successful in reducing total GHG emission in this sector. The current focus of implementing renewable energy is on the electricity sector thanks to the low cost and superior simplicity of photovoltaic panels and also the versatility of electric power. However, total electrification of world's energy consumption doesn't seem to be feasible in near future.

For low temperature applications, solar thermal collectors (a currently mature technology) and photovoltaic driven high temperature heat pumps (as an emerging technology) are promising solutions. However, due to the recent availability of these compact heat pumps in the market, and the recent cost reduction in PV systems, solar thermal collectors' suitability for low temperature applications needs to be re-investigated. A PV driven heat pump might be a more suitable option.

Current high temperature heat pumps are limited to 150˚C with a heat source at 90˚C (Jutsen, Pears et al. 2017) which is not always available. Two third of medium temperature heat usage in industrial applications is below 200˚C (Eisentraut and Brown 2014). Advanced solar thermal collectors with high efficiency can provide energy to these applications without requiring any waste heat (Gajic, Karwa et al. 2015, Rahou, Mojiri et al. 2016). Current evacuated tubes and evacuated flat plate collectors are able to efficiently generate heat of up to 200˚C.

In this paper, we introduce a new high temperature thermal collector design that is currently being developed at RMIT University to achieve an operating temperature of above 200˚C with more than 50% thermal efficiency. Such a high temperature collector can also be suitable for temperatures below 200˚C since it can help to reduce the size of heat exchangers and increase the energy density in the balance of systems.

2. Compound parabolic Concentrators

Compound parabolic concentrators (CPCs) are low optical-concentration, non-imaging solar collectors capable of concentrating solar radiation onto a thermal absorber without the requirement for diurnal sun tracking (Winston 1974). The original optimised non-imaging concentrator was developed during particle physics research, as a method of detecting faint Cherenkov light from electrons travelling faster-than-light in a medium (Hinterberger and Winston 1966).

Winston (Winston 1970) showed that the concentration ratio of a CPC is $C=n/\sin\theta_A$, where n is the refractive index of the medium surrounding the absorber, and θ_A is the half acceptance angle. In fact, the CPC guarantees the highest possible solar concentration for any desired acceptance angle (Rabl 1976). They are also capable of collecting circumsolar and some diffuse radiation (Mcintire 1979). This makes them very attractive for use in non-tracking roof-mounted solar collectors capable of producing medium-high temperature heat.

With the trough of the CPC aligned in the East-West direction the collector can be designed to balance the desired level of solar concentration and the requirement for hours of light capture (acceptance angle). Alternatively, seasonal tracking can be introduced to allow higher concentration ratios to be utilised throughout the year. With the trough of the CPC aligned in the East-West direction, the collector can be designed to capture solar energy for 7 hrs per day at concentration ratios in the order of 1.9. This is sufficient to ensure thermal outputs in excess of 200°C.

There are a number of different types of CPC geometries, where the configuration is dependent on the shape of the absorber (e.g. flat, fin or tubular). In the case of a circular absorber, the reflector is divided into the following two sections; the reflector and the involute. The method for generating the CPC geometry to suit a circular absorber geometry was presented by (Kim, Balkoski et al. 2013), and has been adopted in this work. In the current work, a thermal-optical optimisation of the CPC geometry was performed using a program written in Matlab, which considers the transmission and absorption of solar energy, optical losses due to the receiver–reflector gap, and the thermal losses.

3. External CPC collector

In an external CPC (eCPC) collector, an evacuated absorber tube is located at the focal line of a CPC mirror. In this case, the concentrated light from the CPC mirror transmits through the glass tube and then strikes the absorber within it. We designed and fabricated such an eCPC collector as the first step towards a high temperature non-tracking solar thermal collector. The specifications of the tested eCPC are presented in Table 1.

The fabricated eCPC collector was tested in the solar lab at RMIT University in Melbourne and the results are presented in Figure 2. In this figure, theoretical dashed line indicates the efficiency values predicted by modelling and simulation. The solid target line is the efficiency that is desired and achievable by a carefully engineered CPC collector. Such a CPC collector is predicted to deliver >200˚C heat at minimum 50% efficiency.

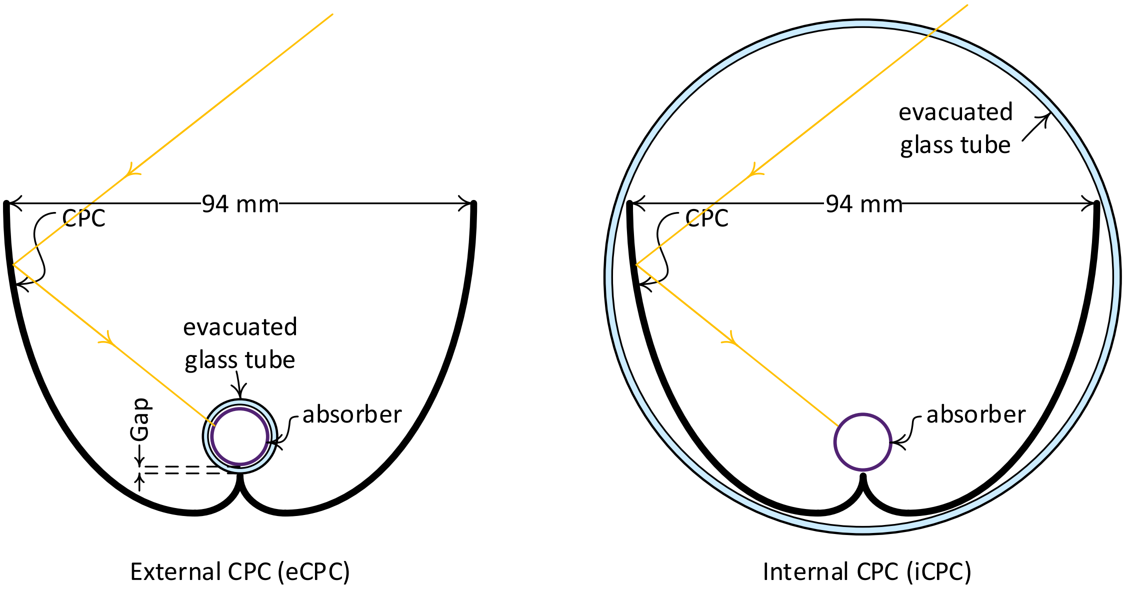

Figure 1. External and internal CPC conceptual designs with the same absorber size

Table 1. eCPC collector specifications

Parameter	Value
Absorber OD	16 mm
Glass tube OD	25 mm
Glass tube thickness	1.5 mm
Gap	4.5 mm
CPC half acceptance angle	27˚
Mirror reflectivity	91%

The measurement of the eCPC design was conducted on 3 iterations of the collector. In all iterations, the design of the eCPC remained unchanged. However, efficiency loss mechanisms of every iteration were identified and addressed for the following iteration. Iteration#2 used CPC mirrors with higher reflectance that lead to improve its optical efficiency. Iteration#3 used a better manifold insulation and minimised heat losses to achieve higher thermal efficiency. The stagnation temperatures of every iteration have also been presented for each curve.

Iteration#3 achieved the modelled efficiencies at low temperatures but underperformed at higher temperatures. This can be due to the

1. poor quality of the selective surface leading to higher emissivity
2. poor quality of vacuum in evacuated tube receiver
3. heat loss increase through the thermal insulation layer around the manifold.

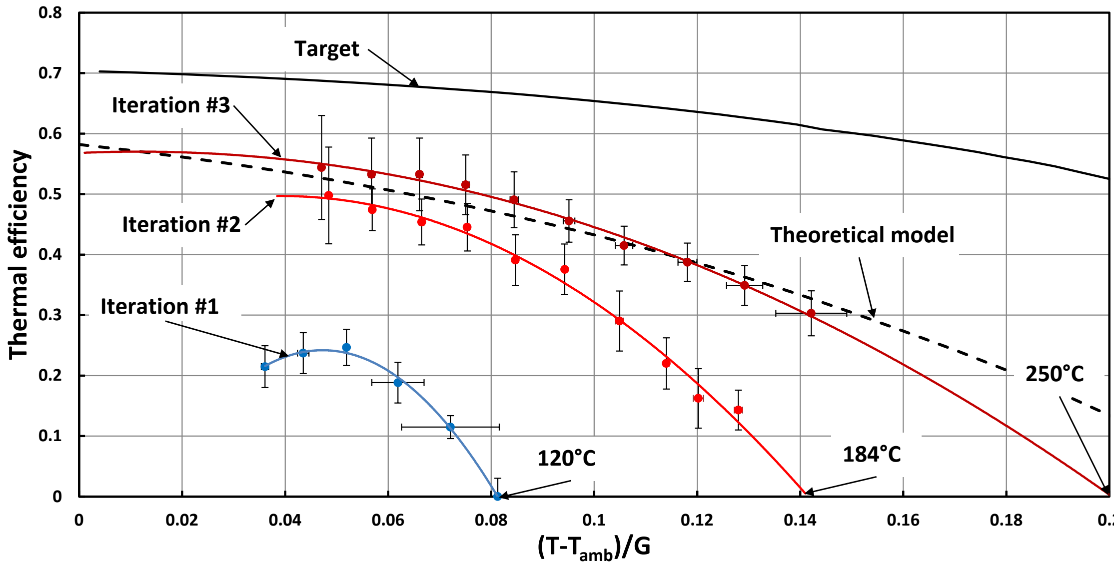

Figure 2. The eCPC efficiency measurement results

There are some inherent drawbacks in the eCPC design:

- The glass envelope of the evacuated tube absorber has a thickness of 1.5 mm. A clearance between the glass and the absorber tube is essential to prevent a thermal bridge between them due to the possible absorber sagging. This increases the gap size (space between the mirror cusp and absorber tube) of the CPC significantly leading to optical losses.
- The concentrated light strikes the glass tube at oblique angles. Due to the curvature of the glass tube, the light beam can deviate from the path to strike the absorber tube leading to an increase in optical losses.
- The CPC mirrors need an extra glass cover to be protected against environmental effects such as rain and dust otherwise the cleaning process can be cumbersome. An extra glass cover incurs further reflection losses.
- There is no standard mass manufacturing process for this design. This prevents the design from being cost competitive.

Such issues form the motivation for following an alternative approach and re-design the CPC collector based on an internally integrated CPC mirror.

4. Internal CPC collector

The general concept of an internal CPC collector has been presented in Figure 2. This design eliminates the issues related to eCPCs mentioned in the previous section. The glass envelope acts as a vacuum tube as well as a protective cover for the CPC mirrors. It doesn't interfere with the CPC and the absorber leading to a significantly smaller gap size. Also, there are standard methods of mass manufacturing such evacuated tubes around the world with durable vacuum and low cost components. In order to quantify the optical performance of the iCPC collector, we conducted a series of ray tracing simulations that are briefly discussed here.

4.1. Designing the iCPC

In order to design the iCPC configuration, we created a Matlab code that calculates the sun angles at different locations throughout the day and over the year. This is because CPCs are non-tracking single axis concentrators that need to be carefully designed and oriented to meet a desired outcome such as maximum energy during the year. The Matlab code uses standard solar angle equations to calculate the projected altitude angle. This is shown in Figure 3.

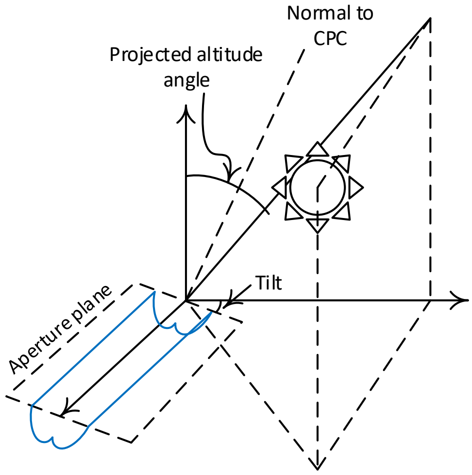

Figure 3. The project altitude angle

The iCPC collector was intended to be designed in such a way that allows for at least 7 hours of beam radiation collection on the "worst" day of the year without active tracking. This is driven by the acceptance angle of the CPC. Choosing the acceptance angle, gap size, and the absorber diameter, we generated a CPC shape that matches the internal diameter of a standard glass tube used in evacuated tube technology.

4.2. Optical Modelling of the iCPC collector

The parameters used in the ray tracing model are listed in Table 2. If only optical efficiency is to be optimised, the thermal receiver should be installed tangent to the cusp of the CPC to avoid an optical gap loss. However, a gap is introduced to avoid a thermal short-circuit between the CPC and the thermal absorber. In the absence of air in the glass tube, simply avoiding a contact between the two objects would be enough to reduce heat losses. In reality, mechanical limitations such as installation tolerances or the difficulty in achieving a manufactured CPC shape with a sharp cusp will produce a gap between the concentrator and the absorber. A theoretical CPC will contain a sharp cusp, and two parabolic curves defining the curvature. As roll-forming is the manufacturing process chosen for the prototype, an approximation of the CPC with concatenated circumferences was also analysed in the ray tracing optics, to simulate a more realistic concentrator.

Table 2. The dimensions and specifications of the model used in ray tracing

Source	
Source shape	Pillbox
Cone angle	0.26°
Number of rays	150K
Source width	102 mm
Mirror	
Reflectivity	92%
Scattering	No
Aperture width	96 mm
Acceptance angle	68°
Glass tube	
External OD	102 mm
Thickness	2.8 mm
Refractive index	1.52
Internal transmission	99.4% per 25mm
Absorber	
Absorptivity	100%
OD	20 mm

To simplify the model, a single wavelength of 550 nm was defined for the solar source. Hence, this is only a geometrical analysis discarding spectral effects. The number of rays was proven sufficient with a ray-independency analysis. We conducted the simulation varying the lateral incidence angle of the iCPC collector (as defined in Figure 4). Hence, this simulation is only partially modelling the iCPC behaviour since the longitudinal incidence angle is not being taken into account.

For each angular deviation, the optical efficiency was calculated as the ratio between the energy impacting the absorber and the total radiation striking the outer diameter of the glass.

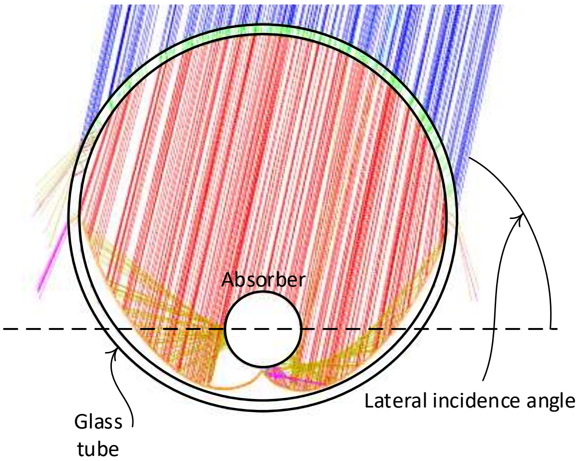

Figure 4. The definition of lateral incidence angle in the ray tracing simulation

4.3. Thermal modelling of the iCPC collector

We developed a Matlab code to calculate the operating temperature of the absorber as a function of time of the year. This model takes the solar angle, collector tilt angle, and the optical efficiency of the collector into account. However, the weather data is not included yet. Since radiation is the only loss mechanism, we can say that,

$$\sigma \varepsilon \pi D_a (T_a^4 - T_g^4) = (\eta_{opt}\alpha - \eta_{th}) G D_g \cos\theta .$$

The parameters of this equation are defined in Table 3. T_g was assumed to be the ambient temperature of 25°C and the G was assumed to be 1000 W/m^2.

Table 3, Thermal modelling parameters

σ	Stefan-Boltzman constant
ε	emissivity of the absorber
D_a	absorber OD
T_a	absorber surface temperature
T_g	glass tube temperature
η_{opt}	optical efficiency
α	absorber absorptance
η_{th}	Thermal efficiency
G	Solar radiation
D_g	Glass tube OD
θ	incidence angle

5. Results

The variation of solar projected altitude angle over the year is presented in Figure 5. It has been presented for half of the year at a latitude of 30˚ in northern hemisphere. In this figure the CPC has a half acceptance angle (AA) of 34˚ and is titled by the local latitude angle. The area between the blue and red horizontal lines is the time of the day that the CPC collector is capable of collecting the beam radiation. The distance between the two vertical dashed lines is 7 hours.

It is seen in this figure that that if the CPC is titled by the local latitude angle, the duration of beam collection in winter and summer solstice are the same although the length of the day is significantly different. It is also seen that the collector can harness the beam for more than 7 hours per day for most part of the year.

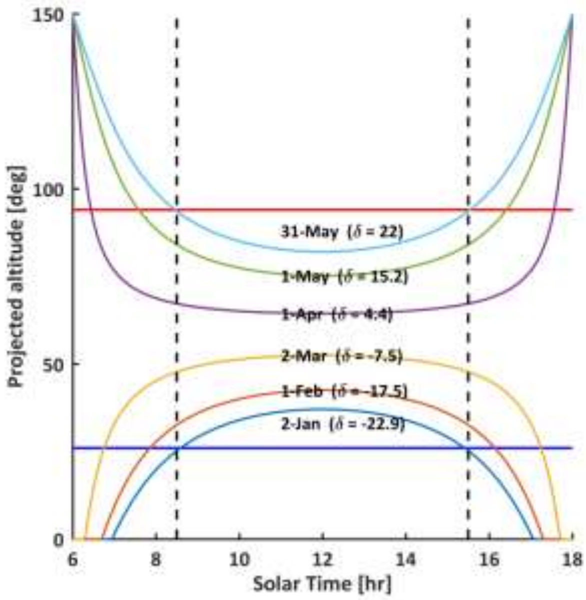

Figure 5. The projected incidence angle on a CPC; AA = 68, latitude = +30, Tilt angle = Latitude

Figure 6 shows the optical efficiency of the system as a function of lateral incidence angle from normal to just below the half acceptance angle. The optical efficiency peak is 77% at normal incidence angle and decreases to about 70% at 60˚ incidence angle. Geometrical losses, Fresnel reflection from the glass envelop, and non-ideal mirror reflectivity are the major loss mechanisms. The optical efficiency drops rapidly for larger incidence angles.

It is observed that the half acceptance angle of the systems is 2 to 4 degrees less than the designed one. This is due to the fact that the glass envelope has a steering effect on the incoming light beam and induces a variation on the actual incidence angle on the CPC mirror. This is an important finding showing that the optics of this system can be highly sensitive to parasitic factors increasing its optical losses.

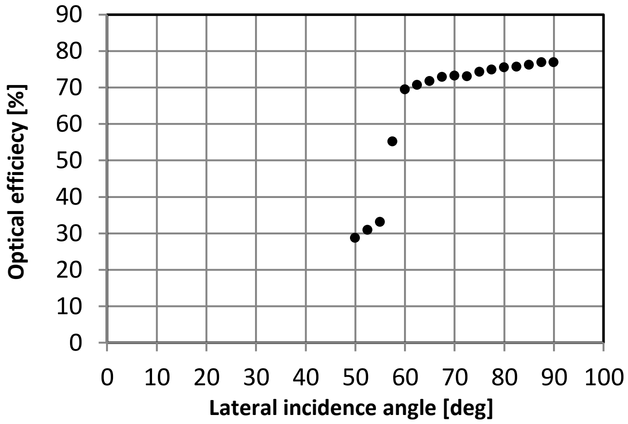

Figure 6. The optical efficiency of the CPC collector simulated using ray tracing

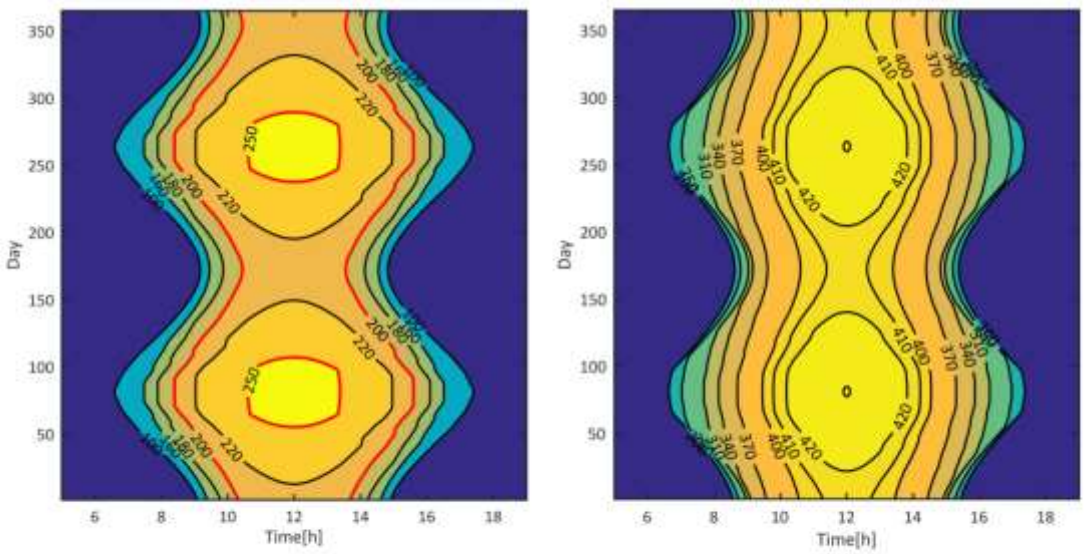

Figure 7. (a) The operating temperature of the absorber with 50% thermal efficiency; (b) the stagnation temperature of the absorber over the year. G = 1000 W/m^2

Using the simulation tool explained in the previous section, we calculated the absorber temperature at different time of the year. The absorber temperature at 50% thermal efficiency and stagnation situation are presented in Figure 7a and b respectively. In Figure 7a the 200 and 250˚C contour lines have been highlighted with red colour to show that 50% thermal efficiency above 200˚C is achievable for significant part of the day throughout the year. Around summer and winter solstice the collector is capable of reaching 250˚C at 50% thermal efficiency.

The stagnation temperature of the absorber reaches at least 410˚C throughout the year with peaking during winter and summer solstice reaching 430˚C. This is well above the stagnation temperature of a flat plate vacuum collector such as that manufactured by TVP that has a stagnation temperature of 330˚C.

A comparison between the proposed iCPC and the eCPC design has been provided in Table 4

Table 4, Comparison between the eCPC and the iCPC designs

Design parameter	eCPC	iCPC	Comment
Acceptance angle	54°	68°	Manufacturing inaccuracies reduce the actual acc. angle
Absorber OD	16 mm	20 mm	-
Aperture width	112.6 mm	94 mm	-
Truncated CPC height	85 mm	45 mm	-
Stagnation temperature	250°C	430°C	The low stag. temperature of eCPC was due to the low quality of vacuum and the selective surface.

6. Conclusion

In this paper, we have introduced the design of an integrated internal CPC solar collector that can generate heat at above 200˚C with a minimum thermal efficiency of 50%. The collector doesn't need tracking and can be installed at a fixed angle depending on the load requirements. The collector is expected to have a stagnation temperature of 430˚C. This design has the potential to be mass manufactured using standard methods and shos promising potential to meet the heat demand of process heat applications.

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