OPTICAL ANALYSIS AND COMPARISON OF SINGLE-SIDED ABSORBER CPC (SSACPC) AND DOUBLE-SIDED ABSORBER CPC (DSACPC) COLLECTORS

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ABSTRACT

This paper presents an optical analysis and comparative study of external concentrating single-sided absorber CPC (SSACPC) and double-sided absorber CPC (DSACPC) collectors designed to enhance the collection of solar radiation. This analysis forms part of a much larger study aimed at reducing system losses, improving thermal performances and temperature enhancement of evacuated heat pipe collectors for use in higher temperature applications such as solar powered refrigeration systems. Ray trace analysis using different incident angles of solar radiation, optical efficiency and related optical losses, angular acceptance and flux distribution of the designed external concentrating reflectors for the full and truncated SSACPC collectors were computed using a two dimensional ray-trace technique and compared to that of a full and truncated DSACPC collectors.

1. INTRODUCTION

Greenhouse gas emissions are a global societal issue, which results from the accumulated use of fossil fuels. In order to reduce the accumulation of greenhouse gases, renewable energy technologies must make a significant contribution to global energy production [DTI, 2003]. In Northern Maritime climates such as the UK, solar water heating systems have the potential to significantly reduce fossil fuel use and thus green house gas emissions. Evacuated tube solar water heaters have proven to be more efficient compared to flat plate collectors within the Northern Maritime climates, capable of delivery 5-15% more thermal energy per year [DGS, 2005]. One of the greatest barriers to the wide scale application of solar heating and cooling systems is installation and system costs [Nchelatebe et al., 2008) resulting from the use of numerous evacuated tube solar collectors to attain higher temperatures. However, concentrators offer cost reduction opportunities. CPCs were considered due to their higher output temperature and improved system performance resulting from their abilities of concentrating both beam and diffuse radiation, which is not possible from other imaging collecting devices [Rabl, 1976, Pramuang , 2005]. The integration of external concentrating collectors to increase solar collection can improve the thermal performance, reducing system cost resulting in a unit area of the reflector, lower than the cost of evacuated tubes only. Optical analysis using simulation models plays an important role and is useful for predicting theoretically the performances of solar collectors before embarking any experimental investigation [Tchinda, 2007, Zacharopoulos et al., 2008]. The design, simulation and optical analysis of externally incorporated CPC reflectors for a single-sided and double-sided evacuated heat pipe absorbers to enhance solar collection, thus the potential of improving performance has been investigated and the results presented in this paper.

2. SYSTEM DESIGN

Two externally integrated CPCs solar collectors; single-sided and double-sided evacuated heat pipe absorbers with half acceptance angles of 30^o and a geometrical concentration ratio of 2 were designed. A 30^o designed acceptance half-angle (θ_a) with a north-south orientation was selected as it allowed maximum collection at northern latitude per day and year with no tilt adjustment. The SSACPC collector consisted of an evacuated heat pipe with an effective absorber width of 63.7mm with an aperture width of 130mm. The DSACPC collector consisted of a modified evacuated heat pipe with the front and back (left and right) absorbing surface giving an effective absorber width of 2 x 63.7mm with an aperture width of 260mm.

Truncation of the upper part of the reflectors was carried out to 51.3% and 47.8% for the SSACPC and DSACPC collectors respectively while maintaining the same geometrical concentration ratio of 1.85 for both collectors to allow for comparative evaluation. The relative evacuated heat pipe absorber area compared to the aperture area of the concentrating collectors resulted to a reduction in heat losses and the good reflectivity of the aluminium sheet (0.91) employed also minimised optical losses. Side section views of the full and truncated SSACPC and DSACPC collectors with their respective evacuated heat pipe collectors are illustrated in Figures 1 and 2 respectively (all dimension in mm) and the specifications (physical and geometric characteristics) for each of the collectors are detailed in Table 1.

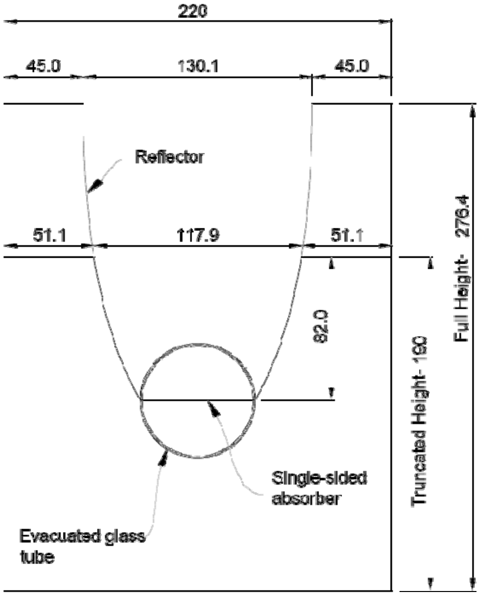

Figure 1: Side section view of the full and truncated SSACPC collectors

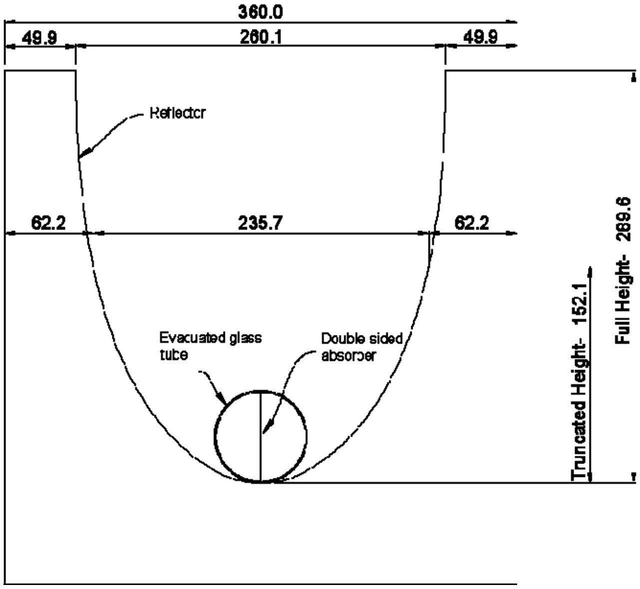

Figure 2: Side section view of the full and truncated DSACPC collectors

Table1: Geometric characteristics of the full and truncated SSACPC and DSACPC collectors

	Full and truncated fabricated reflector profile	
Characterisation	**Full SSACPC collector**	**Full DSVCPC collector**
Half Acceptance Angle (^{o})	30^o	30^o
Original Concentration ratio	2	2
Original absorber width (mm)	63.7	2 x 63.7
Original Aperture width (mm)	130	260
Original reflector height (mm)	168	290
Original height to Aperture ratio	1.3	1.1
	Truncated reflector (51.3%)	**Truncated reflector (47.8%)**
Truncated concentration ratios	1.85	1.85
Truncated aperture width (mm)	117.9	235.7
Truncated reflector height (mm)	82	152
Truncated height to Aperture ratio	0.69	0.64
Reflector-absorber gap (mm)	3	3
Reflector material	Aluminium	Aluminium
Reflectivity of reflector	0.91	0.91

In each of the design configurations, a 3mm gap was created between the evacuated heat pipe tube and the bottom of the reflector to avoid thermal conduction. The criteria for the selection and design of the SSACPC and DSACPC collectors were based on; their theoretical calculated higher concentrations ratios, their lower material and fabrication costs and the suitability for Northern European Maritimes climates. Additional advantages offered by the DSACPC collector include; same amount of absorber material as the SSACPC collector, a more efficient use of the absorber material due to radiation reaching the front and back of the absorber and no back heat losses.

3. RAY TRACE ANALYSIS

Ray trace techniques and solar simulation were employed to evaluate the CPC designs at different incidence angles and their optical performance and flux distribution on the absorbering surface determined and compared. In each design, shown (Figure 3 and 4), equally spaced rays (50) across the collector aperture were traced. The results show that almost all the rays perpendicular to the aperture of the collector (Figure 3 (a, b) and 4 (a, b) reach the absorber creating mirror symmetry between the left and right sides of the reflector and the absorber. The incoming rays are however concentrated on the left and right hand edge of the full and truncated SSACPC collectors and on the lower absorber section of the full and truncated DSACPC collectors.

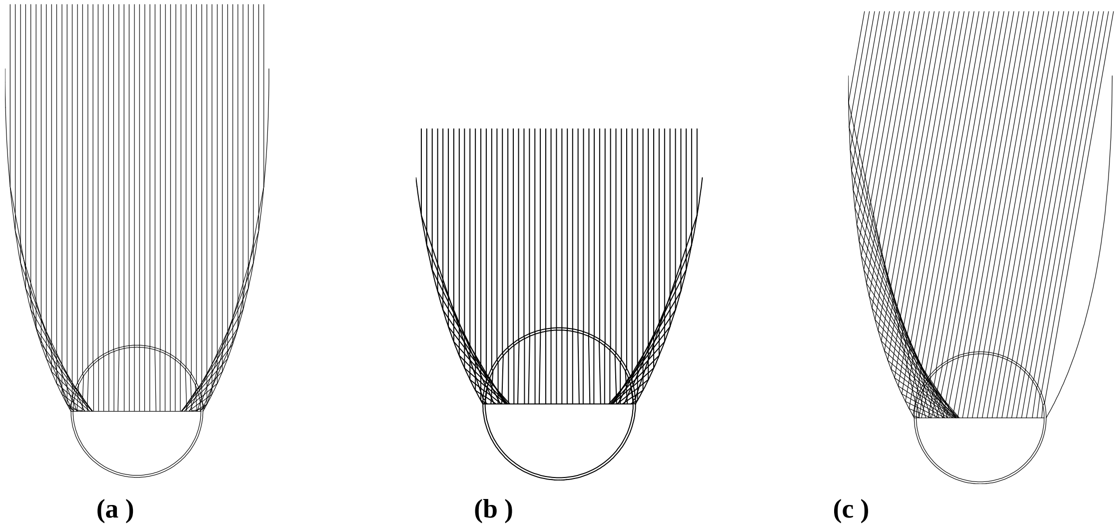
(a) (b) (c)

Figure 3: Ray trace diagram for the full and truncated SSACPC profiles with solar radiation perpendicular (a and b) and at 15^o (c) to the aperture of the collector

The ray trace diagrams at 15^o incident angle (figure 3 (c) and 4 (c) showed that rays are spread across the absorber sections but not covering the full absorber and are more concentrated to the left side of both the full and truncated SSACPC collectors. The lower left of the absorber section in the full and truncated DSACPC collectors has more rays than the upper and right portions of the absorber. Thus symmetry no longer exists between the left and the right sides and the upper and lower portion of the absorbers of the SSACPC and DSACPC collectors respectively. The concentration of the incident rays on the absorber of the full and truncated DSACPC collectors is higher compared to that of SSACPC collectors and this resulted from rays hitting both sides of the absorber and fewer of the rays missing the absorber and exiting the collector. At 15^o incident angle, rays intersected the reflector fewer times before reaching the absorber resulting to higher energy input on the absorbers with lower optical losses. As the incident solar angle increased to 30^o, fewer of the rays reached the absorber of the full SSACPC and DSACPC collectors compared to their equivalent truncated SSACPC and DSACPC collectors but are concentrated on one small focus creating very high energy flux levels.

Both the full and truncated SSACPC collectors had more of its rays concentrated on the right edge of the absorber while the full and truncated DSACPC collectors had more rays concentrated on the upper absorber section after multiple reflections by the left side of the reflector with more rays concentrated to the left. However, the right side of the absorber of the full DSACPC collector has an uneven ray distribution from the upper to the lower absorber section. Symmetry of the ray's distribution on the absorber of both collectors no longer exists and the frequency of reflection and refraction of incoming rays before reaching the absorber was highest, hence the average energy of each ray as it reached the absorber was minimum at 30^o incident angle, resulting in reduced optical efficiency.

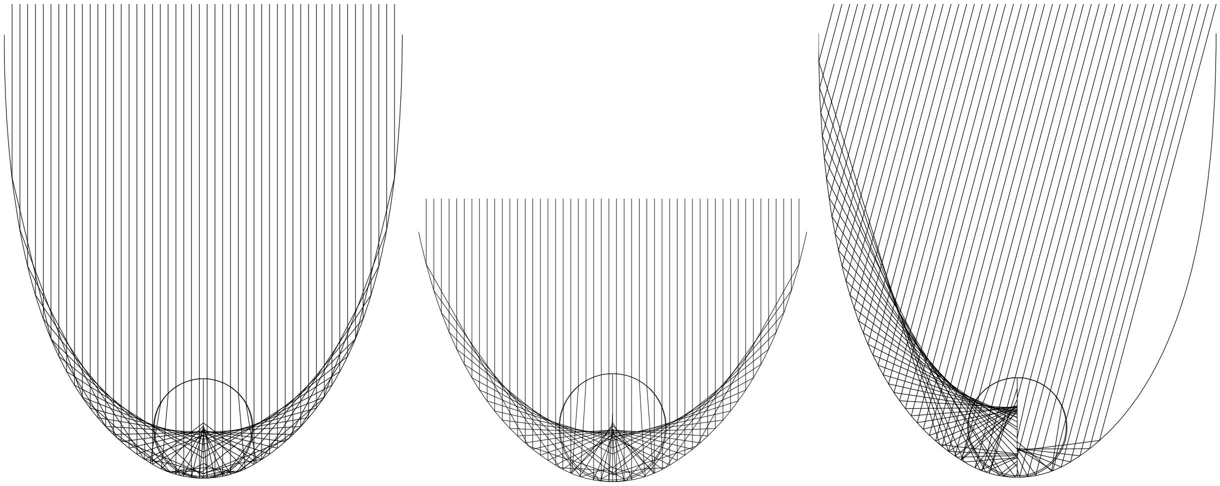
(a) (b) (c)

Figure 4: Ray trace diagram for the full and truncated DSACPC profiles with solar radiation perpendicular (a and b) and at 15^o (c) to the aperture of the collector

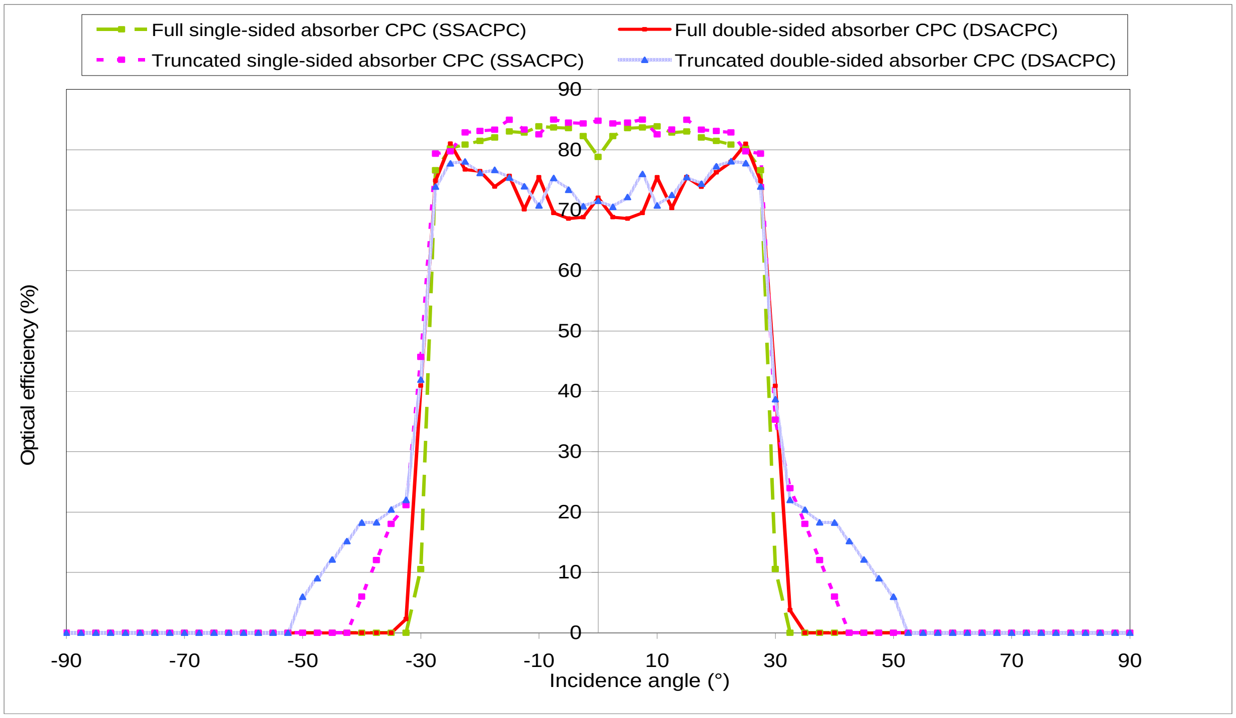

Figure 5: Comparison of the optical efficiency of the full and truncated SSFCPC and DSVCPC collectors at different incidence angles

4. OPTICAL CHARACTERIZATION (EFFICIENCY, ANGULAR ACCEPTANCE AND FLUX DISTRIBUTION)

A comparison of the optical efficiency of the full and truncated SSACPC and DSACPC collectors at different incidence angles (-90° to 90°) of solar radiation is illustrated in Figure 5.

The optical efficiency of the full SSACPC collectors increases from 78.8% at 0^o incident angle to 83.9% at 10^o incident angle but drops to 10.6% at 30^o incident angle whereas the optical efficiency of the full DSACPC collector increases from 72.1% at 0^o incident angle to 81% at 25^o incident angle before dropping to 40.9% at 30^o incident angle. Both systems exhibited a reduction in optical efficiency across a range of incident angles resulting from reflection and refraction of incident rays on the glass surface of the evacuated tubes. A comparative analysis of overall optical performance between 0^o and 30^o incident angles showed a 4.9% reduction in optical efficiency recorded by the full DSACPC collector compared to SSACPC collector. The optical efficiency of the truncated SSACPC collector increases from 84.8% at 0^o incident angle to 85% at 15^o and dropped to 35.3% at 30^o whereas the optical efficiency of the truncated DSACPC collector increased from 71.5% at 0^o to 77.8% at 25^o before dropping to 38.7% at 30^o. An overall 8% further reduction in optical efficiency was recorded by the truncated DSACPC collector compared to truncated SSACPC collector between 0^o and 30^o incident angles. A comparative analysis of overall optical performance of full and truncated SSACPC collectors at different incidence angles show a higher optical efficiency (corresponding to lower optical losses) recorded by the truncated SSACPC collector compared to the full SSACPC. The truncated SSACPC collector recorded a 3.3% higher optical efficiency compared to the full SSACPC collector over the range of incident angles 0° to 30°. A similar analysis for the full and truncated DSACPC collectors over the range of incident angles 0° to 30° show a similar optical efficiency.

The optical efficiency of the full CPCs reflectors dropped to zero slightly above their design acceptance half-angle of 30° with the optical efficiency of the full DSACPC collector dropping to zero at 35° and 32.5° for the full SSACPC collector. The greater view factor of the truncated systems permitted more energy collection outside of the design acceptance half-angle (30°). The truncated SSACPC collector collected 3.8% more energy compared to the full SSACPC collector between 30° and 42.5° before dropping to zero at 42.5° whereas the truncated DSACPC collector collected 11.4% more energy compared to the full DSACPC collector before dropping to zero at 52.5°. At 42.5° incident angle, the truncated DSACPC collector had a 4.7% higher optical efficiency compared to the truncated SSACPC collector and a further 10.6% greater between 42.5° to 52.5°incidence angles. Higher optical efficiencies are realised by the truncated SSACPC and DSACPC collectors compared to their full version and the overall

4.9% and 8% further increase in optical efficiencies recorded by full and truncated SSACPC collector compared to full and truncated DSACPC collector respectively are as a result of a reduced average number of multiple reflections by the rays before reaching the absorber due to reduced reflector height, increase acceptance of beam and diffuse radiation reaching the absorber and decreased heat losses per aperture area.

The comparison of angular acceptance of incidence solar radiation to the aperture of the full and truncated SSACPC and DSACPC collators is shown in Figure 6. It can be seen that; the full DSACPC collector had 100% of all incident rays reaching the absorber at seven different incidence angles (5^{o}, 10^{o}, 15^{o}, 20^{o} 22.5^{o}, 25^{o} and 27.5˚) compared to the full SSACPC collector with 100% of all incident rays reaching the absorber only at five different incidence angles (0^{o}, 5°, 7.5°, 12.5^{o} and 17.5^{o}). The truncated DSACPC collector had 100% of the incoming rays reaching the absorber at six different incidence angles (7.5^{o}, 10^{o}, 15^{o} 20^{o}, 22.5^{o} and 25^{o}) compared to the truncated SSACPC collector with 100% of incoming rays reaching the absorber only at four different incidence (0^{o}, 2.5^{o}, 12.5^{o} and 15^{o}).

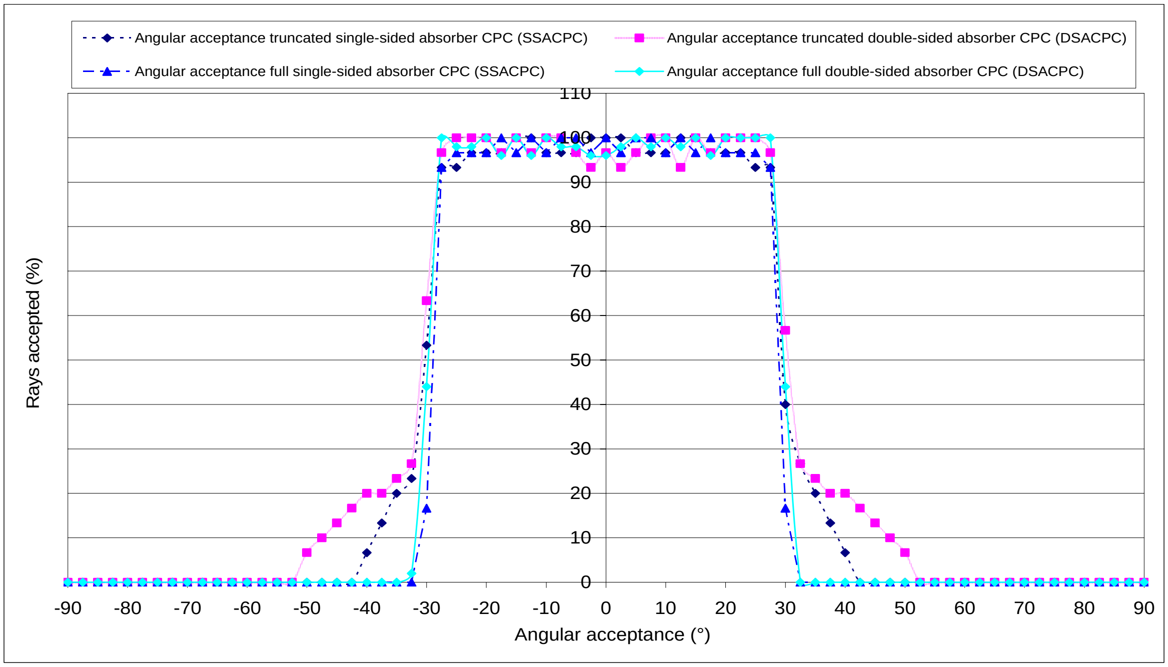

Figure 6: Comparison of the angular acceptance of incidence solar radiation for full and truncated SSACPC and DSACPC collectors at different incidence angles

Irradiation distribution diagrams (IDDs) showing the solar flux distribution on the absorber of each of the collector were generated using ray trace technique and 10.000 equally spaced rays were traced at different incidence angles to the aperture for each collector. Figures 7 and 8 illustrate the distribution patterns of the energy flux distribution on the absorber of each of the full SSACPC and DSACPC collectors at different incidence angles. A variation in energy concentration was realised across the absorber resulting from variation of incidence angles of insolation on the aperture of the collectors. The different distribution patterns resulted from the reflection and refraction of incoming rays at different surfaces. Low energy peaks on the absorber resulted from low flux intensities emerging from either multiple intersecting of the rays with the reflector or rays missing the absorber and exiting to the external environment. The low and high energy peaks should result in lower and higher temperatures points on the absorber. In Figure 7, it can be seen that three peaks with energy concentration of 1862W/m^2 each were recorded by the full SSACPC collector while two peaks in energy concentration of 27023W/m^2 was recorded on the left and right side of the full DSACPC collector at 0^{o} incidence angle. As the incidence angles increased to 7.5^{o} and 10^{o}, the full SSACPC collector had one peak of energy concentration of 2820W/m^{2}and 3289W/m^2 respectively compared to two peaks in energy concentration at each incident angle with energy concentration of 2996W/m^2 and 3081W/m^2 on the left side of the absorber and 3149W/m^2 and 3176W/m^2 on the right side of the absorber recorded by the full DSACPC collector respectively.

The peak values on the left and right sides of full DSACPC collector at 0^{o} and 7.5^{o} incidence angles were higher than that recorded by the full SSFCPC collector while the full SSACPC collector recorded one peak energy concentration of 3289W/m^2 at 10^{o}, 3875W/m^2 at 15^{o}, 4924W/m^2 at 20^{o}, 5844W/m^2 at 22.5^{o} and 4075W/m^2 at 30^{o} incidence angles. The full DSACPC collector had two peaks in energy concentration, one on either side of the absorber and the peak energy recorded on the left side of the absorber was 2574W/m^2, 1074W/m^2, and 660W/m^2 at 15^o, 20^o and 22.5^o respectively whereas 4038W/m^2, 5165W/m^2, 6164W/m^2 and 2403W/m^2 at 15^o, 20^o, 22.5^o and 30^o respectively were recorded as peak energy concentration on the right side of the absorber (Figures 8 and 9).

The peak values recorded by the absorber of the full SSACPC collector between 15^o to 30^o incidence angles were higher than the peak values recorded on the left side of the absorber of the full DSACPC collector but lower than the peak values on the right side of the full DSACPC collector at 15^o to 22.5^o and higher at 30^o incidence angles of solar radiation. From the figures presenting the flux distribution on the absorber, it is evident that varying the incidence angle on the collector aperture resulted in different energy concentration across the absorber with high energy concentration further exploited by controlling heat transfer fluid flow only in these areas with a temperature improvement. It was also determined that, at 0^o incident angle, up to 93.1% more energy peak concentration was recorded on the left and right side of the absorber of the full DSACPC collector compared to the peak in energy concentration on the absorber of the full SSACPC collector. At 7.5^o incident angles, 9.42% and 8.88% more peak in energy were recorded on the left and right sides of the absorber of full DSVACPC collector compared to the peak in energy on the absorber of full SSACPC collector. Similar comparative studies based on the overall averaged peak in energy concentration collected from 0^o to 30^o incident angles showed a 24.3% and 48.6% higher peak in energy concentration collected by left and right sides of the full DSACPC collectors respectively compared to full SSACPC, representing a 72.8% higher peak in energy concentration collected by the full DSACPC collector compared to the full SSACPC collector and this resulted from the collection of energy on both sides of the absorber.

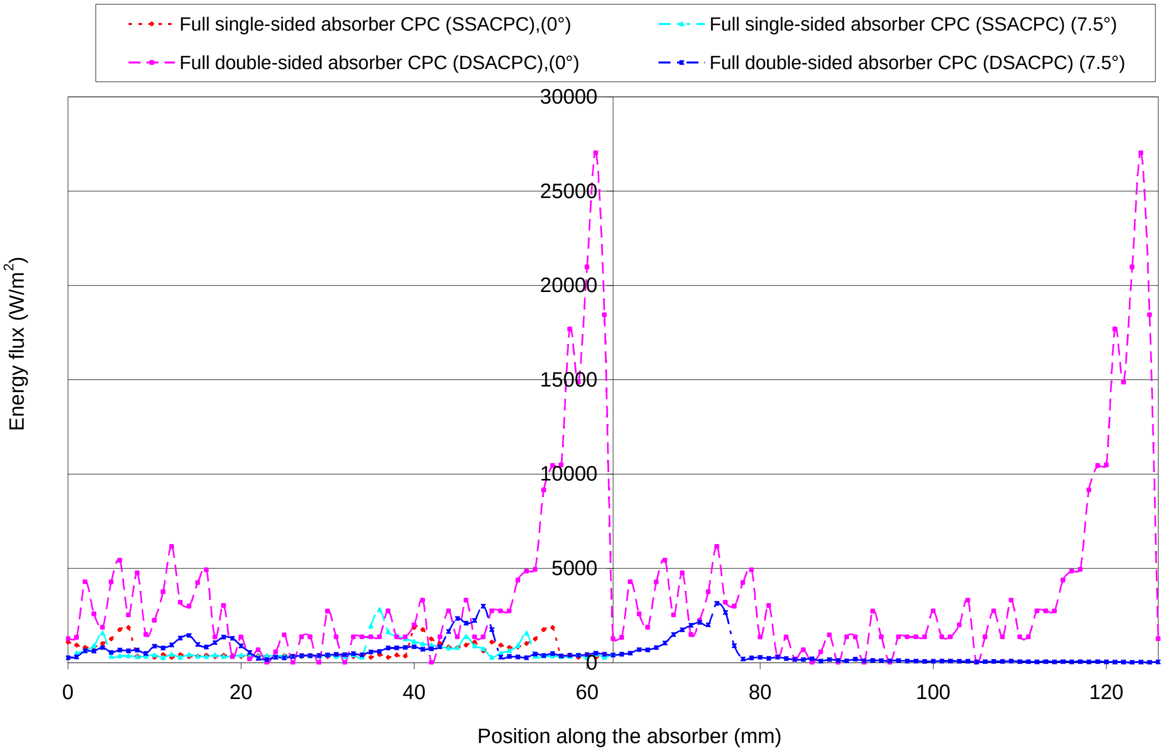

Figure 7: Energy flux distribution on the absorber of the SSACPC and DSACPC collectors at 0^o and 7.5^o incident angles of solar radiation

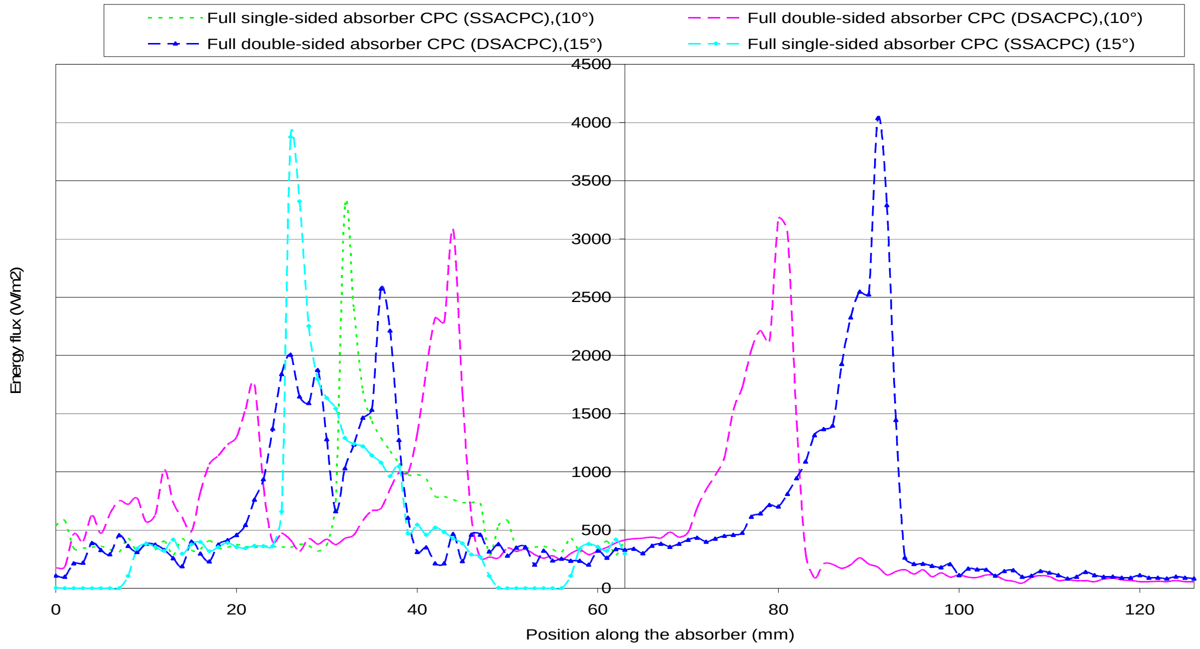

Figure 8: Energy flux distribution on the absorber of the SSACPC and DSACPC collectors at 10^{o} and 15^{o} incident angles of solar radiation

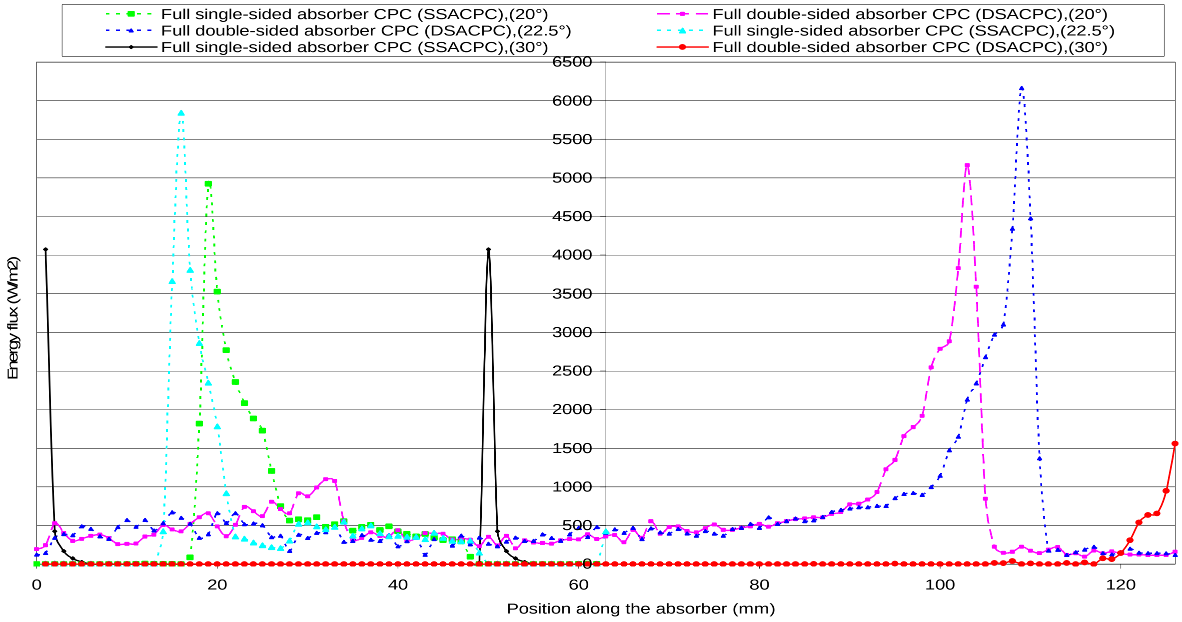

Figure 9: Energy flux distribution on the absorber of the SSACPC and DSACPC collectors at 20^{o}, 22.5^{o} and 30^{o} incident angles of solar radiation

5. CONCLUSION AND SUMMARY OF RESULTS

Full and truncated SSACPC and DSACPC collectors with an evacuated heat pipe collector were optically modeled, analysed and compared using a computer based ray tracing technique. The investigation studied the optical performances, angular acceptance of incidence solar radiation and flux distribution on the absorber of each system at different incidence angles. From the simulation analysis a number of conclusions were determined;

- With incident solar radiation perpendicular to the aperture of the collectors, rays are concentrated onto the left and right absorber edge of the full and truncated SSACPC and on the lower absorber section of DSACPC collectors with mirror symmetry existing on the right and the left sides of the absorber.
- An increase in incidence angle resulted in a non-symmetrical distribution of energy over the reflector. This equally resulted in loss of flux-symmetry distribution between the left and the right sides of the

absorber with the lower absorber section of the full and truncated DSACPC and left absorber section of full and truncated SSACPC collectors having more rays than the upper and right parts of the absorber.

- The concentration of the incidence rays on the absorber was much higher in the full and truncated DSACPC compared to the full and truncated SSACPC due to rays hitting both sides of the absorber and fewer rays missing the absorber and exiting the collector.
- It is evident that the truncated DSACPC and SSACPC collectors have higher optical efficiency (lower optical losses) and angular acceptance than the full DSACPC and SSACPC collectors. In total, the truncated SSACPC had 3.3% higher optical efficiency than the full SSACPC from 0° to 30° incidence angles whereas the analysis and comparison of the full and truncated DSACPC collectors over the range of incident angles 0° to 30° show a similar optical efficiency.
- An overall 8% lower optical efficiency was realised by the truncated DSACPC collector compared to truncated SSACPC collector. The use of concentrating reflectors collected more solar radiation resulting in higher energy peak on the absorber of the DSACPC collector compared to the SSACPC collector. These higher peaks in energy resulted from increased radiation incident on both sides of the absorber of the DSACPC collector compared to only one side of the absorber of the SSACPC collector.
- Truncated DSACPC and SSACPC collectors for higher temperature applications can be much cheaper and can provide higher temperatures than using only evacuated heat pipe collectors and if the reflector material used can operate for a longer period of time without degradation, than the overall cost of solar thermal heating and cooling can be substantially reduce.

6. REFERENCES

[1] DTI, 2003, Energy White Paper: Our Energy future-Creating a Low Carbon Economy, The stationary Office, UK.

[2] Nchelatebe ND, Smyth M, Lo S & Jayanta DM. Short-term performance evolution of a novel retro-fit heat exchanger for solar water heating systems. ‘The 2nd International Conference on Renewable Energies and Water Technologies (CIERTA 2008) and the 5th edition of the International Renewable Energy and Water Technologies Exhibition’, Almeria, Spain, 2008.

[3] Tchinda, R. Thermal behavior of solar air heater with compound parabolic concentrator. Energy conversion and Management, 2008; 529-540

[4] Zacharopoulos A, Jayanta DM, Trevor JH, Smyth M. CPV reflectors for enhanced solar radiation collection of an evacuated tube solar water heater. World Renewable Energy Congress X and Exhibition, Glasgow, Scotland, 2008.

[5] Rabl A. Optical and thermal properties of compound parabolic concetrators.Solar energy 1976;18:497-511.

[6] Pramuang S, Exell RHB.Transient test of a solar air heater with a compound parabolic concetrators.Renew energy 2005;30:715-728.