Optics and Heat Transfer for Asymmetric Compound Parabolic Photovoltaic Concentrators for Building Integrated Photovoltaics

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Abstract

Concentration of solar energy onto photovoltaic materials reduces overall system cost when concentrator cost is less than the displaced photovoltaic (PV) material. Concentration provides higher solar radiation intensity at the PV material increasing electrical power generation per unit PV area. Systems of asymmetric compound parabolic photovoltaic concentrators (ACPPVC) have been designed, fabricated and experimentally characterised for building façade integration in the UK. The ACPPVC system has an acceptance half-angle of 50° and 0° leading to a geometrical concentration ratio of 2.01. In house built Finite Element codes were used for Optics and heat transfer (CFD analysis) of the line-axis solar energy systems. Systems of air filled ACPPVC have been modelled for;

- single trough ACPPVC-50 with a range of solar radiation intensities incident at the aperture cover,
- three trough ACPPVC-50 with constant solar radiation intensities at the aperture, and
- five trough ACPPVC-50 incorporating a range of
  - solar radiation intensities incident at the aperture cover
  - open channel geometries adjacent to the aperture cover for different inlet air velocities including natural convection, and
  - open air channel geometries adjacent to the rear aluminium plate and adjacent to the aperture cover for different inlet air velocities.

Convective behaviour inside a single trough and between consecutive troughs together with the effect of solar cell operating temperature is presented. Predicted optical efficiency was 85% for a wide range of solar incidence angles. A 95°C solar cell surface temperature was predicted for incident radiation of 1000 Wm\(^{-2}\). Forced convection at the rear aluminium plate and at the glass aperture cover reduced the solar cell surface temperature by 35°C.

The three trough ACPPVC-50 system was studied experimentally using a continuous solar simulator. The three trough ACPPVC-50 achieved a fill factor of 65% for a range of solar radiation intensities incident at the aperture cover. Two five-trough ACPPVC-50s incorporating modified reflector troughs were characterised experimentally under outdoor environmental conditions. Electrical output and temperature effects were investigated for;

- A PV system using an asymmetric compound parabolic concentrator.
- A control PV system using the same cell spacing without a concentrator.
- An ACPPVC-50 system with and without concentrators in real time for
  - different PV series combination
  - different realistic conditions.

The maximum power available from the ACPPVC-50 increased by 65% (i.e. a power ratio of 1.65) compared to the theoretical power ratio of 2.01. A power loss analysis indicated that the ACPPVC-50 can achieve a power ratio of up to 1.94 when solar cell spacing is reduced from 52 mm to 2 mm.
Notes on Access to Contents

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2.6.1.1 Ray trace diagrams for (a) untruncated ACPPVC-50, (b) truncated ACPPVC-50, (c) untruncated ACPPVC-60 and (d) truncated ACPPVC-60. No of incoming rays were 50 and the solar radiation intensity incident at an angle of $60^\circ$.

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2.6.3.1 Examples of ray trace diagram for truncated ACPPVC-50 for solar incidence angles on the aperture cover glass of (a) $42^\circ$, (b) $60^\circ$, (c) $75^\circ$ and (d) $89.5^\circ$ to the vertical. 50 rays are included for each ray trace diagram.

2.6.4.1 Ray trace diagrams for an ACPPVC-50 with the reflector profile approximated by different numbers of planar reflector elements (a) 3 elements, (b) 5 element, (c) truncated 3 element, and (d) truncated 5 element system. For each illustrative ray trace diagram the solar incidence angle was $60^\circ$ to the vertical.

2.6.5.1 Ray trace diagrams for (a) $0^\circ$ (b) $5^\circ$, (c) $10^\circ$ inclined untruncated ACPPVC-50 and (d) a $10^\circ$ inclined truncated ACPPVC-50. 50 rays are included for each ray trace diagram.

2.7.1.1 Angular acceptance and optical efficiency for an untruncated ACPPVC-50.

2.7.1.2 Variation of angular acceptance and optical efficiency for an untruncated ACPPVC-60.

2.7.1.3 Variation of angular acceptance and optical efficiency for a truncated ACPPVC-50.

2.7.1.4 Variation of angular acceptance and optical efficiency of an untruncated ACPPVC-50 with reflectors comprised of 5-planar elements.
2.7.1.5 Variation of angular acceptance and optical efficiency of an untruncated ACPPVC-50 with reflectors comprised of 3-planar elements.

2.7.1.6 Variation of angular acceptance and optical efficiency of a truncated ACPPVC-50 with reflectors comprised of 5-planar elements.

2.7.1.7 Variation of angular acceptance and optical efficiency of a truncated ACPPVC-50 with reflectors comprised of 3-planar elements.

2.7.1.8 Variation of optical efficiency with solar incidence angle and number of planar elements used to comprise reflector profiles.

2.7.1.9 Variation of angular acceptance and optical efficiency for ten degree inclined untruncated ACPPVC-50 for different solar incidence angle.

2.7.1.10 Variation of angular acceptance and optical efficiency of a ten degree inclined truncated ACPPVC-50.

2.8.1.1.1 Energy distribution across the aperture of a truncated ACPPVC-50 for solar incidence angles of 42°, 60° and 89.5° to the vertical. The incident solar radiation intensity was 1000 Wm$^{-2}$.

2.8.1.2.1 Energy absorbed along the lower reflector of a truncated ACPPVC-50 for solar incidence angles of 42°, 60°, 75° and 89.5°. The incident solar radiation intensity was 1000 Wm$^{-2}$.

2.8.1.2.2 Energy absorbed along the upper reflector of a truncated ACPPVC-50 for solar incidence angles of 60°, 75° and 89.5°. The incident solar radiation intensity was 1000 Wm$^{-2}$.

2.8.1.2.3 Predicted energy absorbed at the reflectors of a truncated ACPPVC-50 inclined at 10° and 0° to the vertical. The incident solar radiation intensity was 1000 Wm$^{-2}$ incident at an angle of 60° to the vertical.

2.8.1.3.1 Energy distribution across the photovoltaic absorber of a truncated ACPPVC-50 for solar incidence angles of 42°, 60°, 75° and 89.5° to the vertical. The incident solar radiation intensity was 100 Wm$^{-2}$.

2.8.1.3.2 Absorbed energy at the PV absorber of a truncated ACPPVC-50 with reflectors comprised of three and five planar elements. The incident solar radiation intensity was 1000 Wm$^{-2}$ incident at an angle of 60° to the vertical.

2.8.1.3.3 Absorbed energy at the absorber of an untruncated ACPPVC-50 inclined at 10° and 0° to the vertical. The incident solar radiation intensity was 1000 Wm$^{-2}$ incident at an angle of 65° to the vertical.

2.8.1.3.4 Absorbed energy at the PV absorber of a truncated ACPPVC-50 inclined at 10° and 0° to the vertical. The incident solar radiation intensity was 1000 Wm$^{-2}$ incident at an angle of 65° to the vertical.

2.8.2.1.1 Energy distribution of the truncated ACPPVC-50 along the aperture cover for diffuse solar radiation. The incident diffuse solar radiation intensity was 100 Wm$^{-2}$.

2.8.2.2.1 Predicted energy absorbed at the lower reflector for three diffuse solar radiation distributions. The incident diffuse solar radiation intensity was 100 Wm$^{-2}$.

2.8.2.2.2 Predicted energy absorbed at the upper reflector for three diffuse solar radiation distributions. The incident diffuse solar radiation intensity was 100 Wm$^{-2}$.
2.8.2.3.1 Predicted energy absorbed at the photovoltaic absorber for three different diffuse solar radiation distributions. The incident diffuse solar radiation intensity was 100 Wm$^{-2}$.

3.3.1 Asymmetric compound parabolic concentrator for building integration in the UK with acceptance-half angles of 0° and 50°.

3.4.1.1 Aperture cover specification for the ACPPVC-50 system.

3.4.2.1 Computer generated asymmetric compound parabolic reflector profile (a) untruncated system (pointing out the truncation line) (b) truncated system.

3.4.2.1.1 Aluminium reflector support for the asymmetric compound parabolic photovoltaic concentrator.

3.4.2.1.2 Modified reflector support design for outdoor experimental characterisation of the ACPPVC-50.

3.4.4.1 Back plate design for indoor experimental characterisation of an ACPPVC-50 system.

3.4.4.2 Cross-sectional view of back plate and three trough reflector support.

3.4.4.3 Top view of rear aluminium plate of the ACPPVC-50 used for outdoor experimental characterisation.

3.4.4.4 Cross-sectional view of five trough reflector support.

3.4.5.1 Adjustable wooden supporting frame for the ACPPVC-50 system: (a) base frame (b) top frame with 10-mm gap between reflector end and glass cover (c) top frame with 20-mm gap between reflector end and glass (d) top frame with 30-mm gap between reflector end and glass cover.

3.5.1.1 Top and bottom reflector mould

3.5.2.1 A 6-mm thick aluminium reflector support.

3.5.3.1 Construction of the rear aluminium back plate. Four aluminium plates of 3mm thick were screwed to a single aluminium plate.

3.5.3.2 Locating reflector supports on to the rear aluminium back plate.

3.5.3.3 Reflector supports placed on the rear aluminium back plate.

3.5.4.1 Solar cell connections (a) series connection to increase voltage (b) parallel connection to increase current (c) combination of series and parallel connections to increase current and voltage.

3.5.4.2 Soldering of front connection of solar cells.

3.5.4.3 Alignment and interconnection of individual solar sells in series. The solar cells were located between two reflector supports during soldering to ensure their accurate positioning.

3.5.5.1 Attachment of mirror reflector to the reflector support. The mirror was attached to a 0.0003 m thick stainless steel back plate.
3.5.5.2 Asymmetric compound parabolic photovoltaic concentrator with mirror reflectors attached to the rear aluminium back plate.

3.5.6.1 Line up of solar cells on the aluminium back plate. Individual solar cells are connected in series.

3.5.6.2 Encapsulation of solar cells with EVA in a vacuum oven.

3.5.6.3 Solar cells encapsulated on to the aluminium back plate clearly showing the replaced solar cell.

3.5.7.1 Placement of detachable reflector troughs on the aluminium back plate with the encapsulated PV cells.

3.5.7.2 The ACPPVC-50 used for outdoor experimental characterisation without the wooden frame or cover glass.

3.5.8.1 Asymmetric compound parabolic photovoltaic concentrator with wooden frame.

3.5.8.2 Internal electrical connections of solar cells through the wooden frame. Each series of solar cells are connected individually to each electrical connector.

3.6.1.1 Fabricated asymmetric compound parabolic photovoltaic concentrator used for indoor experimental characterisation.

3.6.2.1 Top view of the ACPPVC-50 system used for outdoor experimental characterisation.

3.6.2.2 The full Asymmetric compound parabolic photovoltaic concentrator system.

3.6.2.3 Side view of the asymmetric compound parabolic photovoltaic concentrator used for outdoor experimental characterisation.

3.6.2.4 The plan view of the asymmetric compound parabolic photovoltaic concentrator used for outdoor experimental characterisation.

3.6.2.6 The plan view of the 2nd ACPPVC-50 with temperature sensors inside the system.

4.2.2.1 Schematic diagram of a three trough asymmetric compound parabolic photovoltaic concentrator showing energy transfer mechanisms.

4.2.3.1 Example of finite element mesh employed for the simulation of a single trough ACPPVC-50.

4.2.3.2 Example of finite element mesh employed for the simulations of a five trough ACPPVC-50 (a) enlargement of reflective fins, (b) enlargement of reflector back plate junction (c) enlargement of inter-reflector space.

4.3.1 The theoretically predicted isotherms and velocity vectors for a single trough ACPPVC-50 with boundary conditions given in figure 4.2.2.1. The isotherms are at 1°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.05 ms⁻¹. The solar radiation intensity was (a) 200, (b) 400, (c) 600, (d) 800, (e) 1000 and (f) 1200 Wm⁻² incident at an angle 60° to the aperture cover.

4.3.2 Predicted temperature and air velocity in the horizontal x-direction from the midpoint of the PV cell to the glass aperture cover: (a) temperature, (b) velocity.
4.4.1 The theoretically predicted isotherms and velocity vectors for a three trough ACPPVC-50 with boundary conditions given in figure 4.2.2.1. The space between the reflector and the aperture cover is 10-mm. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\). The solar radiation was 1000 Wm\(^{-2}\) incident at an angle 60° to the aperture cover.

4.4.2 Enlarged view of the predicted isotherms and velocity vectors for a three trough ACPPVC-50 shown in figure 4.4.1 with boundary conditions given in figure 4.2.2.1: (a) lower trough, (b) top trough.

4.4.3 Change of temperature and air velocity inside each individual trough of the three trough ACPPVC-50 from the mid point of the PV cell to the aperture cover: (a) temperature, (b) y-component velocity.

4.5.1.1 The predicted isotherms for a five trough ACPPVC-50 with the boundary conditions given in figure 4.2.2.1 for solar radiation intensities of (a) 200 Wm\(^{-2}\), (b) 400 Wm\(^{-2}\) (c) 600 Wm\(^{-2}\) (d) 800 Wm\(^{-2}\) (e) 1000 Wm\(^{-2}\). The air gap between the concentrator and aperture cover is 20-mm and isotherms are at 1°C intervals.

4.5.1.2 Enlarged views of the predicted isotherms and velocity vectors for a five trough ACPPVC-50 for (a) 1\(^{st}\) trough (b) 5\(^{th}\) trough, with boundary conditions given in figure 4.2.2.1. The incident solar radiation at an angle 60° to the aperture cover was 200 Wm\(^{-2}\). The isotherms are at 1°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\).

4.5.1.3 Enlarged views of the predicted isotherms and velocity vectors for a five trough ACPPVC-50 for (a) 1\(^{st}\) trough (b) 3\(^{rd}\) trough, with boundary conditions given in figure 4.2.2.1. The incident solar radiation at an angle 60° to the aperture cover was 400 Wm\(^{-2}\). The isotherms are at 1°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\).

4.5.1.4 Enlarged views of the predicted isotherms and velocity vectors for a five trough ACPPVC-50 for (a) 2\(^{nd}\) trough (b) 4\(^{th}\) trough, with boundary conditions given in figure 4.2.2.1. The incident solar radiation at an angle 60° to the aperture cover was 600 Wm\(^{-2}\). The isotherms are at 1°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\).

4.5.1.5 Enlarged views of the predicted isotherms and velocity vectors for a five trough ACPPVC-50 for (a) 3\(^{rd}\) trough (b) 5\(^{th}\) trough, with boundary conditions given in figure 4.2.2.1. The incident solar radiation at an angle 60° to the aperture cover was 800 Wm\(^{-2}\). The isotherms are at 1°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\).

4.5.1.6 Enlarged views of the predicted isotherms and velocity vectors for a five trough ACPPVC-50 for (a) 4\(^{th}\) trough (b) 5\(^{th}\) trough, with boundary conditions given in figure 4.2.2.1. The incident solar radiation at an angle 60° to the aperture cover was 1000 Wm\(^{-2}\). The isotherms are at 1°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.1 ms\(^{-1}\).

4.5.1.7 Change of (a) temperature, (b) velocity inside ACPPVC-50 in the vertical direction for incident solar radiation intensities of 200, 400, 600, 800 and 1000 Wm\(^{-2}\). The distance is measured between the middle of the lower reflector of the lower most trough and the middle of the upper reflector of the uppermost trough.

4.5.1.8 The predicted average PV cell temperature and average aperture cover temperature for different solar radiation intensities incident at the aperture cover.
4.5.2.1 The predicted isotherms for a five trough ACPPVC-50 with a 10-mm wide front channel between the aperture cover and the reflectors with an inlet air velocity of (a) 0.0 ms\(^{-1}\), (b) 0.2 ms\(^{-1}\), (c) 0.4 ms\(^{-1}\), (d) 0.6 ms\(^{-1}\), (e) 0.8 ms\(^{-1}\), (f) 1.0 ms\(^{-1}\). The isotherms are at 2°C intervals and the incident solar radiation was 1000 Wm\(^{-2}\) at the aperture cover.

4.5.2.2 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with no inlet velocity i.e. natural convection for (a) 1\(^{st}\) trough (b) near to outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.2 ms\(^{-1}\).

4.5.2.3 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with inlet velocity of 0.2 ms\(^{-1}\) for (a) 1\(^{st}\) trough (b) outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.25 ms\(^{-1}\).

4.5.2.4 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with inlet velocity of 0.4 ms\(^{-1}\) for (a) 2\(^{nd}\) trough (b) 4\(^{th}\) trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.5 ms\(^{-1}\).

4.5.2.5 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with inlet velocity of 0.6 ms\(^{-1}\) for (a) 3\(^{rd}\) trough (b) 4\(^{th}\) trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.75 ms\(^{-1}\).

4.5.2.6 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with inlet velocity of 0.8 ms\(^{-1}\) for (a) 1\(^{st}\) trough (b) 5\(^{th}\) trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.0 ms\(^{-1}\).

4.5.2.7 Enlarged view of predicted isotherms and velocity vectors for a 10-mm wide front air channel with inlet velocity of 1.0 ms\(^{-1}\) for (a) 1\(^{st}\) trough (b) 5\(^{th}\) trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.2 ms\(^{-1}\).

4.5.2.8 Change of (a) temperature, (b) velocity inside an ACPPVC-50 in the horizontal direction between middle point of 3\(^{rd}\) solar cell to the aperture cover for different inlet air velocities.

4.5.2.9 The predicted isotherms of five trough ACPPVC-50 with a 20-mm wide front channel adjacent to the aperture cover at inlet air velocity of (a) 0.0 ms\(^{-1}\), (b) 0.2 ms\(^{-1}\), (c) 0.4 ms\(^{-1}\), (d) 0.6 ms\(^{-1}\), (e) 0.8 ms\(^{-1}\), (f) 1.0 ms\(^{-1}\). The isotherms are at 2°C intervals and incident solar radiation was 1000 Wm\(^{-2}\) at the aperture cover.

4.5.2.10 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with no flow i.e. natural convection for (a) 1\(^{st}\) trough (b) near to outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.2 ms\(^{-1}\).

4.5.2.11 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with inlet velocity of 0.2 ms\(^{-1}\) for (a) 1\(^{st}\) trough (b) outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.25 ms\(^{-1}\).
4.5.2.12 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with inlet velocity of 0.4 m/s for (a) 1st trough (b) 5th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.5 m/s.

4.5.2.13 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with inlet velocity of 0.6 m/s for (a) 1st trough (b) 4th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.75 m/s.

4.5.2.14 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with inlet velocity of 0.8 m/s for (a) 2nd trough (b) 4th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.0 m/s.

4.5.2.15 Enlarged view of isotherms and velocity vectors for a 20-mm wide front air channel with inlet velocity of 1.0 m/s for (a) 3rd trough (b) 5th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.2 m/s.

4.5.2.16 Change of (a) temperature, (b) velocity inside ACPPVC-50 in the horizontal direction from the middle of the 3rd solar cell to the aperture cover for different inlet air velocities.

4.5.2.17 The predicted isotherms for a five trough ACPPVC-50 with a 30-mm wide front channel near to the aperture cover at inlet air velocity of (a) 0.0 m/s, (b) 0.2 m/s, (c) 0.4 m/s, (d) 0.6 m/s, (e) 0.8 m/s, (f) 1.0 m/s. The isotherms are at 2°C intervals and incident solar radiation was 1000 W/m² at the aperture cover.

4.5.2.18 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with no inlet velocity i.e. natural convection for (a) inlet (b) near to outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.2 m/s.

4.5.2.19 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with inlet velocity of 0.2 m/s for (a) 2nd trough (b) outlet channel. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.4 m/s.

4.5.2.20 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with inlet velocity of 0.4 m/s for (a) 3rd trough (b) 5th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.5 m/s.

4.5.2.21 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with inlet velocity of 0.6 m/s for (a) 2nd trough (b) 4th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 0.75 m/s.

4.5.2.22 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with inlet velocity of 0.8 m/s for (a) 2nd trough (b) 5th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.0 m/s.

4.5.2.23 Enlarged view of the isotherms and velocity vectors for a 30-mm wide front air channel with inlet velocity of 1.0 m/s for (a) 1st trough (b) 5th trough. The isotherms are at 2°C intervals and the velocity vectors are scaled to the reference vector of magnitude 1.2 m/s.
4.5.2.24 Predicted (a) temperature, (b) velocity inside an ACPPVC-50 in the horizontal direction between the middle node of the 3rd solar cell to the aperture cover for different inlet air velocities.

4.5.2.25 Predicted average PV temperature with inlet air velocity for different front air gap adjacent to the aperture cover.

4.5.3.1 The isotherms of a five trough ACPPVC-50 with 10-mm front and rear channel open to the ambient for inlet air velocities of (a) 0.1 ms⁻¹, (b) 0.5 ms⁻¹, (c) 1.0 ms⁻¹. The isotherms are at 2°C intervals and incident solar radiation was 1000 Wm⁻² at the aperture cover glass.

4.5.3.2 The isotherms of a five trough ACPPVC-50 with 20-mm front and rear channel open to the ambient for inlet air velocities of (a) 0.1 ms⁻¹, (b) 0.5 ms⁻¹, (c) 1.0 ms⁻¹. The isotherms are at 2°C intervals and incident solar radiation was 1000 Wm⁻² at the aperture cover glass.

4.5.3.3 Enlarged view of isotherms and velocity vectors of the 5th trough for a five trough ACPPVC-50 with front and rear air channels of width (a) 10 mm (b) 20 mm. The isotherms are at 2°C intervals and velocity vectors are scaled to the reference vector of magnitude 0.25 ms⁻¹. The incident solar radiation intensity was 1000 W m⁻² at the aperture cover glass.

4.5.3.4 Predicted (a) temperature, (b) velocity inside the ACPPVC-50 in the horizontal direction through the middle of the 3rd solar cell to the aperture cover for different inlet air velocities with a 10-mm wide front and rear air channel.

4.5.3.5 Predicted (a) temperature, (b) velocity inside the ACPPVC-50 in the horizontal direction through the middle of the 3rd solar cell to the aperture cover for different inlet air velocities with a 20-mm wide front and rear air channel.

4.6.2.1 Predicted I-V characteristics of the ACPPVC-50 for incident solar radiation intensities of 200, 400, 600, 800 and 1000 Wm⁻² for a solar cell temperature of 25°C.

4.6.2.2 Predicted I-V characteristics of ACPPVC-50 for different solar cell temperature for the solar radiation intensity of 1000 Wm⁻².

5.2.1.1 The continuous solar simulator used for the indoor experimental characterisation of the developed asymmetrical compound parabolic photovoltaic concentrator unit.

5.2.1.2 Physical and geometrical characteristics of lamps used in the continuous solar simulator (Anon, 2001i).

5.2.1.3 Schematic diagram of the continuous solar simulator.

5.2.1.4 The incident solar flux intensity for the continuous solar simulator when illuminating different areas (a) horizontally, (b) vertically.

5.2.2.1 Spectral distributions for HMI 1200 W/GS lamp used in continuous solar simulator for 100% and 60% rated wattage (Anon, 2001i).

5.3.1 Standard circuit diagram for I-V curve characterisation of PV system (Komp, 1995).

5.3.2 Modified circuit diagram for continuous I-V measurement of photovoltaic system under illumination conditions.
5.5.1 Experimental characterisation of an ACPPVC-50 using the solar simulator.

5.5.2 Enlarged view of the ACPPVC-50 used for indoor experimental characterisation.

5.5.1.1 I-V characteristics for a non-concentrating flat panel with three solar cells connected in series for different incident radiation intensities. The ambient room temperature was 20ºC for all measurements and the solar incidence angle was 0º.

5.5.1.2 I-V characteristics of the ACPPVC-50 for different incident radiation intensities. The ambient room temperature was 20ºC for all measurements and the solar incidence angle was 0º.

5.5.1.3 I-V characteristics for flat non-concentrating panel and the ACPPVC-50 for incident radiation intensity of 250 Wm\(^{-2}\). Room temperature was 20ºC for all the measurements and the radiation incidence angle was 0º.

5.5.1.4 I-V characteristics for the ACPPVC-50 for inclination angles of 0, 5 and 10º. The ambient temperature was 20ºC for all the measurements and the radiation incidence angle was perpendicular to the wooden mounting stand.

5.5.1.5 Indoor experimental characterisation of three flat non-concentrating PV panels using a relay switching card.

5.5.1.6 I-V characteristics of Panel 1 for solar radiation intensity of 200 Wm\(^{-2}\). The ambient room temperature was 20ºC and the radiation incidence angle was 0º.

5.5.1.7 I-V characteristics of Panel 3 for solar radiation intensity of 200 Wm\(^{-2}\). The ambient room temperature was 20ºC and the radiation incidence angle was 0º.

5.5.1.8 I-V characteristics of Panel 4 for solar radiation intensity of 200 Wm\(^{-2}\). The ambient room temperature was 20ºC and the radiation incidence angle was 0º.

5.5.2.1 Variation of instantaneous power with sweep voltage for different radiation intensities of Panel 1. The ambient room temperature was 20ºC and the radiation incidence angle was perpendicular to the PV surface.

5.5.2.2 Variation of instantaneous power with sweep voltage for different radiation intensities of Panel 2. The ambient room temperature was 20ºC and the radiation incidence angle was perpendicular to the PV surface.

5.5.3.1 Frontal view of the location of temperature sensors on the rear aluminium back plate of the three trough ACPPVC-50.

5.5.3.2 Measured temperatures for the three trough ACPPVC-50 with time of exposure to a constant incident radiation of 250 Wm\(^{-2}\).

5.5.3.3 I-V characteristics of the ACPPVC-50 (Panel 2) for different solar cell temperatures at solar radiation intensity of 250 Wm\(^{-2}\).

5.5.3.4 I-V characteristics of the 9-mm wide (Panel 4) solar cell non-concentrating flat panel for different solar cell temperatures for a solar radiation intensity of 250 Wm\(^{-2}\).

5.5.4.1 The variation of fill factor for the ACPPVC-50 with incident solar radiation intensities at constant solar cell temperature of 25ºC.

5.5.4.2 The variation of fill factor with solar cell temperature for Panel 3 at a solar incident radiation intensity of 250 Wm\(^{-2}\).
5.6.1 The variation of electrical conversion efficiency of Panel 1 and Panel 2 for different solar incident radiation intensities.

5.7.1 Variation of power with instantaneous voltage for non-concentrating flat PV panel (Panel 1) and ACPPVC-50 system (Panel 2) at incident solar radiation intensity of 250 Wm\(^{-2}\).

5.7.2 Variation of power with instantaneous voltage for Panel 2 (ACPPVC-50) for different PV cell temperatures with radiation intensity of 250 Wm\(^{-2}\) incident perpendicular to the PV surface.

5.7.3 Variation of power with instantaneous voltage for Panel 4 for different PV cell temperatures with radiation intensity of 250 Wm\(^{-2}\) incident perpendicular to the PV surface.

5.7.4 Variation of output power with output voltage for different inclination angle of the ACPPVC-50 system with solar radiation of 250 Wm\(^{-2}\).

6.2.1 Fabricated ACPPVC-50 systems for outdoor experimental characterisation: (a) System 1 clearly indicating the location of the replaced solar cell (b) System 2.

6.3.1 Block diagram of equipment for testing of PV systems.

6.3.2 Electrical circuit connections used for measuring current and voltage generated by the photovoltaic systems through a 40-channel switching card.

6.3.3 Thermocouple connections at the reflector back plate and at either side of solar cell edge to measure reflector and solar cell temperature respectively.

6.3.4 Thermocouple locations at which the aluminium back plate temperature was measured for System 1.

6.3.5 Thermocouple locations at which the rear aluminium back plate temperature was measured for System 2.

6.4.1 System 1 mounted at an angle 18º from the vertical.

6.4.2 A non-concentrating and an ACPPVC-50 mounted at an inclination angle of 30º to the vertical.

6.4.3 A non-concentrating and an ACPPVC-50 mounted vertically.

6.4.1.1 Measured solar radiation and temperatures for the ACPPVC-50 on the 21st August 2002.

6.4.1.2 (a) I-V curves at different times for different incident solar radiation intensities, (b) variation of short circuit current with solar incidence angle.

6.4.1.3 Shadow created on the right-end solar cell by the wooden frame at 11:54:32 on 21st August 2002.

6.4.1.4 Shadow created on the left-end solar cell by the wooden frame at 14:55:39 on 21st August 2002.

6.4.1.5 Instantaneous power output with voltage developed by System 1 at different times for different incident solar radiation intensities.

6.4.1.6 Change in open circuit voltage and short circuit current with time for System 1.
6.4.1.7 Shadow cast by the wooden frame onto the solar cells at different times of the day.

6.4.1.8 Maximum power output and efficiency of System 1 with incident solar radiation intensity.

6.4.1.9 Diurnal variation of cover glass, aluminium back plate temperature and solar radiation.

6.4.1.10 Measured temperature contours at the aluminium back plate at time (a) 10:30 (b) 12:30 (c) 14:30 (d) 16:30 on the 21st of August 2002.

6.4.1.11 Diurnal variation of solar radiation and back plate temperature at thermocouple positions ‘t5’ and ‘t17’.

6.4.1.12 Diurnal variation of solar radiation and aluminium back plate temperature at thermocouple positions 12 and 15 as shown in figure 6.3.4.

6.4.1.13 Diurnal variation of solar radiation and the aluminium back plate temperature at thermocouple locations t11, t12 and t13 as shown in figure 6.3.4.

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<td>2a</td>
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<tr>
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<td>$G_{sol}$</td>
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<td>current at maximum power point $\text{A}$</td>
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<td>reference current at maximum power point $\text{A}$</td>
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<td>$K_{norm}$</td>
<td>normalization factor</td>
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<td>$P_1, P_2, P_3, P_4$</td>
<td>pressure drop at different points $\text{Nm}^{-2}$</td>
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<td>$P_{\text{max}}$</td>
<td>maximum power $\text{W}$</td>
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<td>$R_L$</td>
<td>load resistance $\text{\Omega}$</td>
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<td>$R_s$</td>
<td>series resistance $\text{\Omega}$</td>
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<td>$R_{sh}$</td>
<td>shunt resistance $\text{\Omega}$</td>
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<td>$R_{\text{th}}$</td>
<td>thermal resistance $^\circ\text{CW}^{-1}\text{m}^2$</td>
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<td>$T_e$</td>
<td>experimental temperature $^\circ\text{C}$</td>
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<td>$T_m$</td>
<td>mean fluid temperature $^\circ\text{C}$</td>
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<td>$T_0$</td>
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<td>simulated temperature $^\circ\text{C}$</td>
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<td>$T_w$</td>
<td>wall temperature $^\circ\text{C}$</td>
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<td>$T_{ct}$</td>
<td>solar cell temperature $^\circ\text{C}$</td>
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<td>$T_{FA}$</td>
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<td>$T_{in}$</td>
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<td>$T_{ext}$</td>
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<td>$T_{ref1}$</td>
<td>first reflector temperature $\text{K}$</td>
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<td>$T_{\text{module}}$</td>
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<td>$T_{\text{outlet}}$</td>
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<td>$T^*$</td>
<td>dimensionless temperature</td>
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<td>$U_0$</td>
<td>flow velocity $\text{ms}^{-1}$</td>
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<td>$U_{\text{int}}$</td>
<td>inlet air velocity $\text{ms}^{-1}$</td>
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<td>$V_{oc}$</td>
<td>open circuit voltage $\text{V}$</td>
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<td>$V_{max}$</td>
<td>voltage at maximum power point $\text{V}$</td>
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<td>$V_{max,ref}$</td>
<td>reference voltage at maximum power point $\text{V}$</td>
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<td>$W_2$</td>
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<td>$Z_0$</td>
<td>incident flux $\text{Wm}^{-2}$</td>
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<td>$Z_1$</td>
<td>absorbed flux $\text{Wm}^{-2}$</td>
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<td>$F'$</td>
<td>first derivative of function</td>
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<td>$M', N'$</td>
<td>points in space</td>
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<td>$T^*$</td>
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<tr>
<td>$Gr$</td>
<td>Grashof number</td>
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<tr>
<td>$Nu$</td>
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<td>$\overline{Nu}$</td>
<td>average Nusselt number</td>
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<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
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</table>
Ra: Rayleigh number
Re: Reynolds number
Re_{\text{min}}: minimum Reynolds number
Re_{\text{max}}: maximum Reynolds number
R_{\text{th,conc}}: thermal resistance of concentrating (ACPPVC-50) system °C\cdot m^2
R_{\text{th,flat}}: thermal resistance of non-concentrating system °C\cdot m^2
I(\theta): distance along tangent from receiver m
I(\psi): tangent of length from the cusp
I_\lambda(\theta): energy contained to corresponding wave length J
\Delta T: change of temperature °C
A/W: solar response AW^{-1}

n: normal vector
a, b, c: constant numbers
diameter
f: focal length m

h: heat transfer coefficient Wm^{-2}K^{-1}
i, j: various components or points
k: thermal conductivity of air Wm^{-1}K^{-1}
k: Boltzmann constant m^2 kg s^{-2} K^{-1}
m: constant
n, p: number
q: electronic charge eV
q: wall heat flux Wm^{-2}
r: radius m
s: stratification parameter

u: velocity component in x-direction ms^{-1}
v: velocity component in y-direction ms^{-1}
x, y, z: co-ordinate

b_a: PV thickness m
b_c: air gap between PV panel and building wall m
b_d: air gap between glazing and PV panel m
b_g: glazing thickness m
b_i: insulation thickness m
b_{in}: inlet air gap m
b_{out}: exit aperture length m

m: parameter
d_{A_i}: elemental area of surface i m^2
d_{A_j}: elemental area of surface j m^2
f_{app}: apparent friction factor in developing flow

f(\theta): angular acceptance function

h_c: heat loss coefficient Wm^{-2}K^{-1}
h_{ab}: heat loss coefficient from absorber Wm^{-2}K^{-1}
h_{ap}: heat transfer coefficient from aperture cover Wm^{-2}K^{-1}
h_{pf}: heat loss coefficient from reflector Wm^{-2}K^{-1}
h_{\text{wind}}: convective heat transfer coefficient from a surface to ambient Wm^{-2}K^{-1}
h_{\text{ground}}: heat loss coefficient from surface to ground Wm^{-2}K^{-1}
h_{\text{min}}: minimum heat loss coefficient from rear aluminium Wm^{-2}K^{-1}
h_{\text{max}}: maximum heat loss coefficient from rear aluminium Wm^{-2}K^{-1}
h_{\text{abs-apt,conv}}: convective heat transfer coefficient from absorber to aperture Wm^{-2}K^{-1}
h_{\text{abs-apt,rad}}: radiative heat transfer coefficient from absorber to aperture Wm^{-2}K^{-1}
h_{\text{abs-ref1,conv}}: convective heat transfer coefficient from absorber to first reflector Wm^{-2}K^{-1}
h_{\text{abs-ref1,rad}}: radiative heat transfer coefficient from absorber to first reflector Wm^{-2}K^{-1}
h_{\text{abs-ref2,conv}}: convective heat transfer coefficient from absorber to sky Wm^{-2}K^{-1}
h_{abs-ref2-rad} \text{radiative heat transfer coefficient from absorber to second reflector } \text{Wm}^{-2}\text{K}^{-1}

h_{abs-sky,rad} \text{radiative heat transfer coefficient from absorber to sky } \text{Wm}^{-2}\text{K}^{-1}

h_{apt-sky,rad} \text{radiative heat transfer coefficient from aperture to sky } \text{Wm}^{-2}\text{K}^{-1}

h_{ref1-apt,conv} \text{convective heat transfer coefficient from first reflector to aperture } \text{Wm}^{-2}\text{K}^{-1}

h_{ref1-apt,rad} \text{radiative heat transfer coefficient from first reflector to aperture } \text{Wm}^{-2}\text{K}^{-1}

h_{ref2-apt,conv} \text{convective heat transfer coefficient from second reflector to aperture } \text{Wm}^{-2}\text{K}^{-1}

h_{ref2-apt,rad} \text{radiative heat transfer coefficient from second reflector to aperture } \text{Wm}^{-2}\text{K}^{-1}

k_f \text{conductivity of fluid } \text{Wm}^{-2}\text{K}^{-1}

k_{entr} \text{entrance friction factor}

n_1 \text{refractive index of medium 1}

n_2 \text{refractive index of medium 2}

n_i \text{refractive index of first medium}

n_r \text{refractive index of second medium}

q_x \text{heat loss along length } x \text{WK}^{-1}

q_{lwr} \text{long wave electromagnetic energy radiation per unit area } \text{Wm}^{-2}

q_i \text{heat loss at surface } i \text{ W}

q_j \text{heat loss at surface } j \text{ W}

q_{lwr_{ij}} \text{long wave radiation exchange between surface } i \text{ and } j \text{ W}

\dot{q}_{abs} \text{absorbed energy} \text{ W}

r_i \text{inner radius} \text{ m}

r_{equ} \text{equivalent radius} \text{ m}

r_{inc} \text{incident vector}

r_{ref} \text{reflected vector}

r_{refl} \text{reflective vector}

r_{refr} \text{refractive vector}

r_0 \text{room temperature} °

v_i, v_j \text{velocity at } i^{th} \text{ and } j^{th} \text{ component} \text{ ms}^{-1}

x_1, y_1 \text{end point}

a' \text{parametric length} \text{ m}

y^* \text{dimensionless co-ordinate}

\overline{h} \text{terminated height} \text{ m}

\bar{l} \text{terminated length} \text{ m}

\dot{q} \text{heat transfer rate} \text{ W}

\overline{x}, \overline{y} \text{terminated co-ordinate}

y^{'*} \text{dimensionless length}

\langle e \rangle \text{element}

\alpha, \psi \text{constant}

\alpha \text{absorptance}

\beta \text{coefficient of volume expansion}

\delta \text{maximum angle with respect to the optics axis} °

\epsilon \text{emittance}

\phi \text{angle} °

\eta \text{efficiency}

\phi \text{tilt angle} °

\lambda \text{friction factor}

\pi \text{constant}

\theta \text{angle} °

\rho \text{density} \text{ kg m}^{-3}

\sigma \text{Stefan-Boltzman constant} \text{ Wm}^{-2}\text{K}^{-4}

\tau \text{transmittance}

\nu \text{reflectance of glass}

\omega \text{hour angle} °

\psi \text{subtended angle at the receiver} °

\alpha_i \text{extinction coefficient of glass} °
\( \beta_0 \) source subtended angle
\( \phi_i \) acceptance half angle for left parabola
\( \phi_r \) acceptance half angle for right parabola
\( \eta_{op} \) optical efficiency
\( \theta_a \) acceptance angle
\( \theta_i \) polar angle at surface \( i \)
\( \theta_j \) polar angle at surface \( j \)
\( \theta_{sc} \) half acceptance angle
\( \rho_0 \) density at \( t_0 \)
\( \rho_m \) mean density of air
\( \nu_{\perp} \) perpendicular component of reflectance
\( \nu_n \) normal reflective coefficient
\( \tau_{\lambda_i} \) wave length dependent transmittance
\( \tau_{\lambda_i} \) transmittance of wave length for particle \( i \)
\( \tau_{\perp} \) parallel component of transmittance
\( \tau_{\perp} \) perpendicular component of transmittance
\( \psi_0 \) angle at centre
\( \theta' \) exit angle
\( \theta_{sc} \) acceptance half-angle
\( \theta_{in} \) incidence angle
\( \theta_{tr} \) transmittance angle
\( \theta_{subc} \) angle
\( \nu_{\parallel} \) parallel component of reflectivity
\( \epsilon_{sky} \) sky emittance
\( \theta_{acc} \) half-acceptance angle
\( \theta_{max} \) maximum angle
\( \theta_{ref} \) reflective angle
\( \theta_{tr11} \) transmittance angle between surface 1 & 2
\( \theta_{tr12} \) transmittance angle between surface 2 & 1
\( \beta_{\text{surface}} \) surface tilt angle
\( \epsilon_{\text{ground}} \) ground emittance
\( \epsilon_{\text{module}} \) PV module emittance
\( \eta_{\text{elec}} \) solar cell electrical efficiency
\( \omega \) vorticity
\( \sum \beta_k \) overall thermal conductivity of air
\( \psi|_{\sigma} \) stream function at the boundary
\( \tau(\theta) \) angular dependence of transmittance
\( \Delta P \) pressure difference
\( \Delta T \) temperature difference
\( \tau(\alpha) \) transmittance-absorptance product
\( \nabla \) gradient
\( \partial \) del operator
\( \times \) vector product
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACPC</td>
<td>asymmetric compound parabolic concentrator</td>
</tr>
<tr>
<td>ACPPVC</td>
<td>asymmetric compound parabolic photovoltaic concentrator</td>
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<tr>
<td>AM</td>
<td>air mass</td>
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<tr>
<td>A/W</td>
<td>Ampere Watt⁻¹</td>
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<td>BEM</td>
<td>boundary element method</td>
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<td>BIPV</td>
<td>building integrated photovoltaics</td>
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<td>CdTe</td>
<td>cadmium telluride</td>
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<td>CFD</td>
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<td>CID</td>
<td>compact iodide daylight</td>
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<td>CIS</td>
<td>copper indium diselenide</td>
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<td>CPC</td>
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<td>CdS</td>
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<td>CST</td>
<td>Centre for Sustainable Technologies</td>
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<td>DUT</td>
<td>device under test</td>
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<td>EAC</td>
<td>extreme asymmetrical concentrator</td>
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<td>EVA</td>
<td>ethylene venyl acetate</td>
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<td>FDM</td>
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<td>HID</td>
<td>high intensity discharge</td>
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<td>I-V</td>
<td>current-voltage</td>
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<td>MaReCo</td>
<td>maximum reflector collector</td>
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<td>MINP</td>
<td>metal-insulator n-type solar cell</td>
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<td>MPP</td>
<td>maximum power point</td>
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<td>N.I.</td>
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<td>NOCT</td>
<td>nominal operating cell temperature</td>
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<td>lead</td>
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<td>passivated-emitter solar cell</td>
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<td>UV</td>
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<td>R1</td>
<td>reflector one</td>
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<td>R2</td>
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<td>RFPC</td>
<td>reverse flat-plate collector</td>
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