# Investigation of the thermal performance of a Concentrating PV/Thermal Glazing Façade Technology

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**Abstract:** Developing effective solar energy technologies which can be integrated into buildings and provide heat, electricity and/or reduce energy needs, is vital to achieving set international targets for renewable energy generation and carbon emissions reduction. While a range of technologies are available at the moment for building integration most of them are simply super-imposed on the building structure rather than becoming an essential part of it. This does not allow for the full advantages of building integration to materialise as it does not reduce costs by replacing conventional building materials and components.

A Concentrating PV/Thermal Glazing (CoPVTG) façade technology that combines glazing based solar concentrating elements, coupled with PV/Thermal absorbers has been developed. The technology is a modular multifunctional building component based on conventional double glazing. It is compatible with traditional façade structures and fenestration framing arrangements which allows easy integration into new and retrofit buildings. It can provide solar generated electricity and air heating through the PV/T absorbers while insulating the building thermally. Depending on the incidence angle the glazing based concentrating elements are designed allow the direct sunlight to enter the building and provide natural daylight when required whilst redirecting it onto the PV/T absorbers to generate electricity/heat when solar gains need to be minimised to reduce cooling demands.

The thermal performance of a 500 mm x 500 mm CoPVTG prototype unit integrated into a conventional window frame has been investigated under controlled conditions in a solar simulator facility. Outlet air temperatures have been measured for a range of inlet temperatures at two different incidence angles of illumination. Generated Hottel-Whillier-Bliss equations show an optical efficiency of 52.6% and a 25.2 W/m$^2$K heat loss coefficient at a 55° incidence angle. At a 20° incidence angle the measured optical efficiency is 43.8% and heat loss coefficient 27.7 W/m$^2$K. The difference in the measured thermal performance is shown to be strongly related to total internal reflection of the light at the surface of the glazing concentrating elements. This is demonstrated by short circuit current measurements of the PVT absorbers.

**Key words:** solar energy; building integration; PV; Thermal; TIR; glazing

## 1. Introduction

Developing effective solar energy technologies which can be integrated into buildings and provide heat, electricity and/or reduce energy needs, is vital to achieving set international target for renewable energy generation and carbon emissions reduction.

Many modern buildings (commercial and domestic) incorporate large glazed areas following architectural expression, providing improved daylighting and wellbeing for their occupants. However conventional fenestration systems have poor insulating properties (compared to traditional constructional elements) resulting in excessive heat loss during cold conditions and increased cooling loads during warmer, sunnier conditions. Integrating advanced glazing with renewable energy generation technologies whilst controlling daylight penetration can create comfortable building internal spaces while ensuring lower energy bills and associated carbon emissions.

Transparent concentrating lens for PV façade building integration have been developed to enable increased electricity generation per unit area of PV material compared to conventional PV panels (Zacharopoulos et al. 2000). Prototype transparent concentrating PV lens were fabricated and experimentally characterised. The results demonstrated that by using the concentrating lens, almost double the amount of electricity per unit of PV material can be generated compared to conventional PV panels (Mallick and Eames, 2007). Daylighting control is possible by tailoring the concentrating lens design to allow incident solar radiation to enter the building at different times during the day. By combining the concentrating lens with a flat glass pane into a double glazing unit and evacuating the cavity, convective heat losses can be eliminated (Zacharopoulos et al. 2011).

Using photovoltaics with solar thermal elements produces a PV Thermal (PVT) solution than can deliver solar thermal heat at levels similar to conventional solar thermal collectors and generate electricity similar to standard PV modules. However a balance needs to be achieved between thermal and electrical energy generation as thermal applications often require higher operational temperatures, whereas the PV module efficiency drops with increasing temperature. Some examples of optimized collector solutions are in development (Dupeyrat et al. 2011a; Dupeyrat et al. 2011b).

Building integrated PV/T collectors offer the following advantages (Jee et al. 2015):

- can provide electricity and thermal energy at the same time;
- they can control overheating of the PV cells
- aesthetics: they have pleasing and innovative design;
- higher life duration;
- space reduction: BIPV/T collector is more compact comparing it to PV cells modules and solar thermal collectors installed separately;
- cost reduction: reduce money on construction materials;
- simplicity of installation;
- protection against elements: protection against weather (wind, rain) and shade against solar radiation;

- environment friendly: BIPV/T collectors provide electricity and thermal energy for its needs reducing gas emission.

This paper presents an experimental investigation into the thermal performance of a Concentrating PV/Thermal Glazing (CoPVTG) façade technology that combines glazing based solar concentrating elements coupled with PV/Thermal absorbers. As a modular multifunctional building component based on conventional double glazing, the CoPVTG is designed to be compatible with traditional façade structures and fenestration framing arrangements, facilitating direct integration into new and retrofit building applications. It can provide solar generated electricity and heated air through the PV/T absorbers while insulating the building thermally (Zacharopoulos et al. 2015). The glazing based concentrating elements are designed to allow the sunlight to enter the building and provide natural daylight when required while redirecting it onto the PV/T absorbers to generate electricity/heat when solar gains need to be minimised to reduce cooling demands.

## 2. The CoPVTG technology

The technology consists of a double glazing panel where the outside pane of glass is shaped into a series of concentrating lens. A thin layer of photovoltaic cells is placed at the focus of the concentrating lens to act as PV/T absorber. The inner pane of glass is a conventional flat pane. Forced air flow between the two glass panes can be used to remove waste heat from the back of the PV and use for space heating or pre-heating purposes. To increase the thermal insulation properties of the technology a third (optional) flat glass pane can be used in front of the concentrating lens pane and the resulting cavity can be filled up with inert gases such as argon or evacuated to eliminate convective heat loss (figure 1).

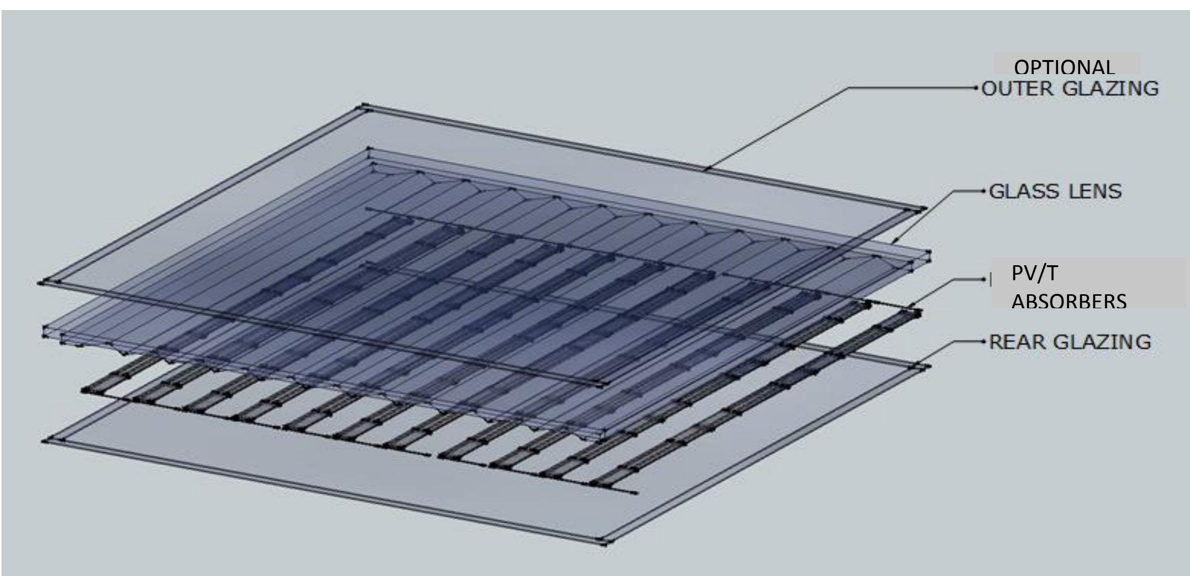


Fig. 1. The CoPVTG technology combining concentrating glass lens with PV/T absorber elements.

Depending on the design of the concentrating lens, a part of the incident solar radiation can reach the PV/T absorbers generating electricity and waste heat while the rest can travel through the unit to provide daylight to the building interior. Using total internal reflection (TIR), the lens design can produce a seasonal effect with more light allowed into the building at incidence angles below a critical angle (i.e. in the winter months) and less light at high incidence angles (i.e. in the summer). Figure 2 demonstrates how by using TIR different amounts of light can be collected onto the PV/T absorbers or transmitted through the glazing unit depending on the incident angle of the solar radiation.

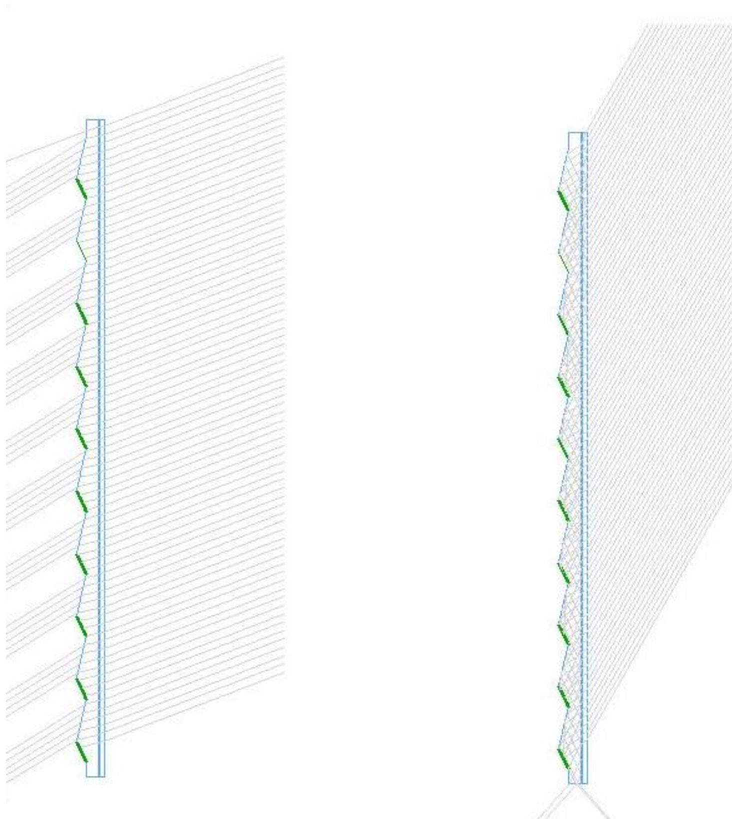

Fig. 2. Ray trace diagrams demonstrating the control of beam solar radiation transmittance by TIR at the concentrating lens. Light incident at 20$^{o}$ (left) and 55$^{o}$ (right) from the perpendicular to the surface of the glazing.

For the 20$^{o}$ incidence angle the PV cells receive the beam radiation light which is directly incident on them. The remaining beam and the larger part of the diffuse radiation are refracted through the lens and transmitted to the back of the unit. At a 55$^{o}$ incidence angle all beam solar radiation is reflected onto the PV/T absorbers by TIR at the back of the glass lens. The few rays missing the absorber at the bottom of the unit are due to edge-effects related to the size of the concentrating glass pane. Depending on the design of the concentrating lens there is a critical incidence angle that switches “on” or “off” the TIR of the solar radiation at the back of the glass lens. Glass lens that can control daylight transmission to the rear of the unit (i.e. into the building) for a specified range of incidence angles of solar radiation can be designed for a given building and geographic location.

The solar radiation that is incident onto the PVT absorbers is absorbed there. Depending on the electrical efficiency of the employed PV cells (typically 16-18%), part of that radiation will be converted to electricity and the remaining will be waste heat which will in turn increase PV operating temperature and reduce electrical output. A forced air flow can be used to remove the waste heat and use it for space or water heating purposes.

## 2.1 The fabricated CoPVTG prototype

A prototype 500mm x 500 mm CoPVTG unit was fabricated using an outer 15 mm (max) thickness concentrating lens pane and an inner 4 mm thickness flat glass pane (figure 3). The concentrating lens were designed to totally internally reflect to their focus all light incident above a 37° angle from the perpendicular to the surface of the glazing. Both glass panes were opti-white for optimum solar transmission. A 25 mm cavity was formed between two glass panes using appropriate size spacers which accommodated the air inlet and outlets at the bottom and top of the cavity respectively (figure 3a). 33 multi-crystalline PV cells configured as 11 strips of 3 cells each were bonded at the focus of the concentrating lens using opti-clear silicon resin. The dimensions of each PV cell were 156 mm x 13 mm. Green coloured cells were used (C-Cell range by LOF Solar) to achieve good aesthetics. A PVC window frame was used to mount the fabricated CoPVTG unit (figure 3a). The frame had a slot cut out along its top and bottom to allow the air to flow through the unit. The air was supplied by flow and return header ducts with slots cut identical to that of the window frame allowing a clear passage of air. The fabricated CoPVTG inserted into the PVC window frame is illustrated in figure 3b.

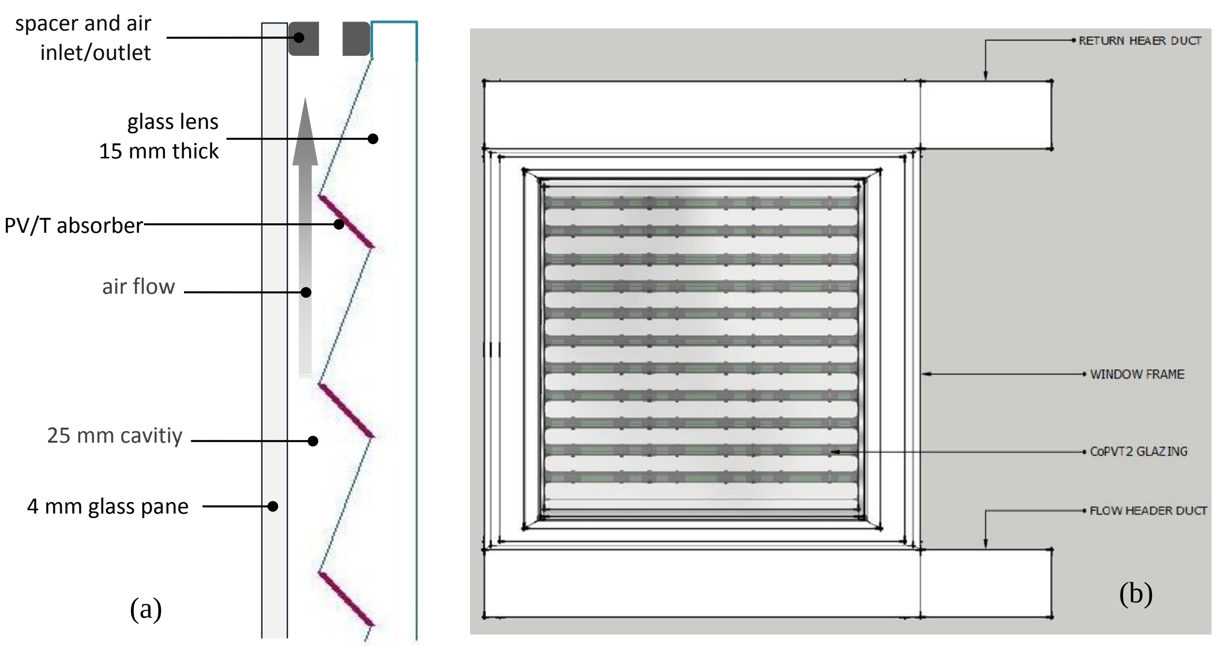


Fig. 3. a) Cross section of the fabricated CoPVTG prototype and b) schematic of the prototype unit inserted into a PVC window frame (right).

Both header and return flow ducts were covered with polystyrene insulation to minimise heat loss. A DC fan was used to produce and control an air flow through the CoPVTG glazing cavity using a power supply. K-type thermocouples were placed inside the glazing cavity to monitor PV cell and concentrating glass temperatures. Further thermocouples were placed inside the header and return ducts to monitor air inlet and outer temperatures.

## 3. Experimental setup and methodology

Using the CST solar simulator (Zacharopoulos et al. 2009) the capability the prototype CoPVTG (figure 4) to generate heat was investigated for two incidence angles of illumination; 20° and 55°. The two angles were selected to be at either side the critical TIR angle of the concentrating lens (figure 4) and correspond to solar altitudes angles that would occur at solar noon on a winter (20°) and a summer day (55°). For each tested incidence angle a series of air inlet temperatures were simulated by using a controllable air heater connected to the inlet of the prototype CoPVTG window. Stagnation temperatures were measured by removing the air flow through the window and allowing it to reach its maximum temperature. A high precision, high temperature Kipp & Zonen CM4 pyranometer was used to measure the illumination intensity on the surface of the prototype. Table 1 provides the test parameters for the two incidence angles. During the tests an Infra-Red (IR) camera was used to visualise the temperature distribution across the front and the back of the prototype. The PV absorber performance was monitored by measuring the short circuit current ($I_{sc}$) and open circuit voltage ($V_{oc}$) of three PV cells connected in series. However as no constant load was connected to the PV cells no electricity was generated during the tests and therefor the total amount of light captured by the PVT absorber was converted to heat.

| Incidence angle of illumination | Illumination intensity[1] ($W/m^2$) | Air flow velocity[2] (m/s) | Ambient temperature[2] (°C) |
|---|---|---|---|
| 20° | 775 | 2.14 - 2.26 | 22.3-26.1 |
| 55° | 503 | 1.98 – 2.04 | 21.9-24.7 |

[1] Average intensity calculated from 5 equally spaced measurements across the aperture of the prototype
[2] Variation of measured parameter during the tests

Table 1. Parameters for the two examined incidence angles of illumination

The instantaneous thermal power and efficiency of the prototype was calculated as:

Thermal power: $$Q = \rho A v c_p (T_o - T_i) \qquad \text{Eq. (1)}$$

Thermal efficiency: $$\eta_{th} = \frac{Q}{G * A} \qquad \text{Eq. (2)}$$

Based on the Hottel-Whillier-Bliss equation for solar collectors the thermal efficiency can be expressed as:

$$\eta_{\mathrm{th}} = F_R(\tau\alpha) - F_R U_L \frac{(\mathrm{T}_m - \mathrm{T}_\mathrm{a})}{\mathrm{G}} \qquad \text{Eq. (3)}$$

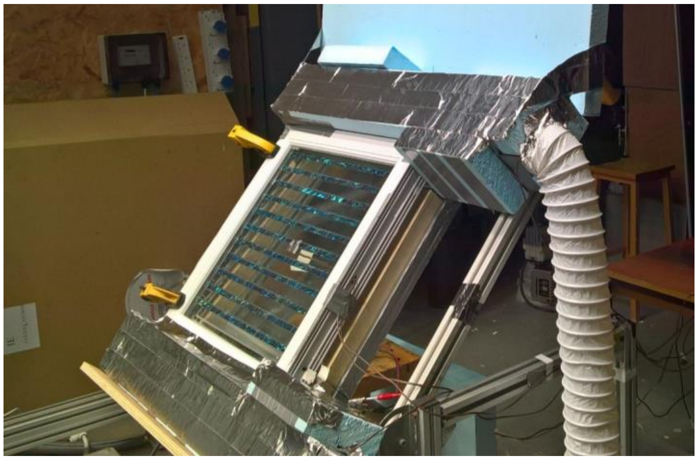

Figure 4. The experimental CoPVTG prototype (left) and a demonstration of TIR at the concentrating lens (right).

## 4. Results and analysis

Figures 5 and 6 present measured temperatures, open circuit voltage and short circuit current variation during the two tests. The prototype was able to heat air for both examined incidence angles. Although the illumination intensity for the 20° test was 1.54 higher than that of the 55° incidence angle, temperature increases across inlet and outlet are similar across the range of examined temperatures. Stagnation temperatures were 39°C and 35°C or 10.3°C and 12.9°C above ambient respectively.

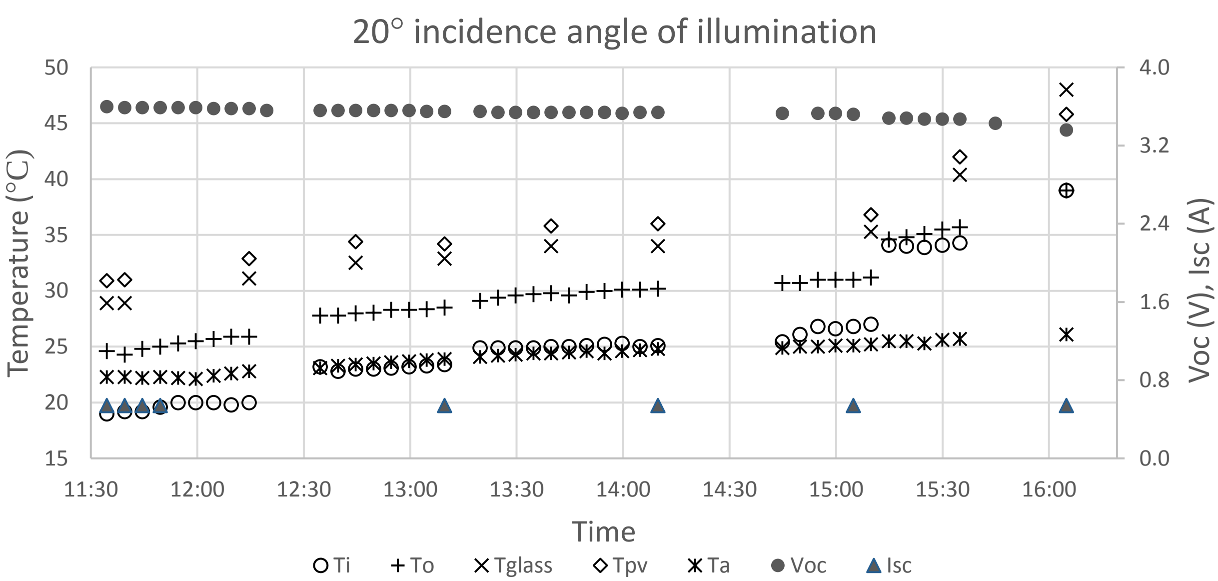


Figure 5. Recorded temperatures, open circuit voltage and short circuit current of the CoPVTG prototype at 20° incidence angle of illumination

Measured PV cell and glass temperatures in both tests are higher than inlet and outlet. However the difference between glass and PV cell temperatures is larger in the 55° incidence angle test. The amount of light that reaches the PVT absorber in the two tests can assessed from the measured short circuit currents. $I_{sc}$ is proportional to the intensity of the light incident on the PV cell and is not affected by temperature. Although illumination intensity for the for 55° was 1.54 lower to that in the 20° tests the measured $I_{sc}$ values for the two tests were almost identical (0.54 A for 20° and 0.55 A for 55°). This demonstrates that TIR is effective in concentrating 1.54 times more incident light onto the PVT absorber which in turn allows the prototype to achieve similar temperature lifts in both tests. Whilst short circuit current remains unaffected by the increase in the operating temperature of the prototype, the open circuit voltage reduces and has a negative effect in the electrical output of the prototype. The $V_{oc}$ measurements at stagnation were 6.7% and 4.5% lower compared to those at the start of the 20° and 55° incidence angles tests respectively. This demonstrates the potential benefit that removing the waste heat can have on the electrical performance of the prototype.

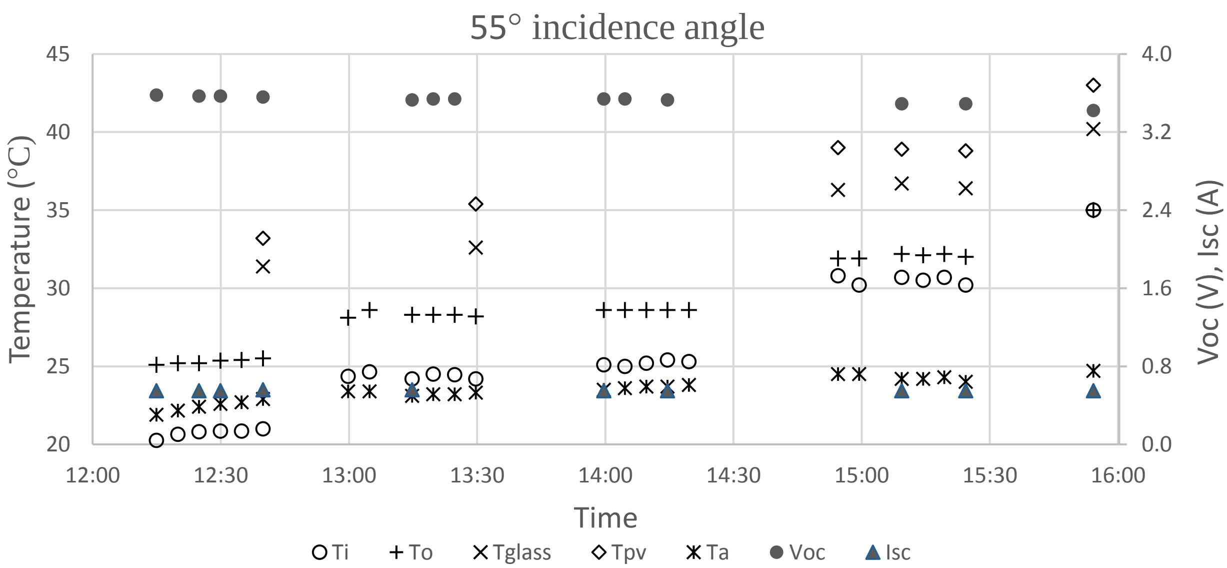


Figure 6. Recorded temperatures, open circuit voltage and short circuit current of the CoPVTG prototype at 55° incidence angle of illumination

Figure 7 shows an IR image of the prototype under test with illumination incident at 20° at 15.35. A distinct two shade linear pattern demonstrates the effect of the PVT absorber capturing the light whilst the clear glass lens surface allow the light to be transmitted through. The maximum temperature on the glass surface is approx. 37.7°C and the lowest approx. 36.6 °C. IR images from the rear of the prototype show a practically uniform temperature distribution of 30.1°C. At the time when the IR images were taken $T_{PV}$ and $T_{glass}$ were 42°C and 40.4°C which indicates a high heat loss rate from both front and rear of the prototype.

The instantaneous efficiency curves for the two incident angles were generated from the measured experimental data and are shown in figure 8. Both curves demonstrate a similar trend of decreasing thermal efficiency with increasing operating temperatures but the prototype has a higher optical (zero-loss) efficiency when the illumination is incident at 55°.

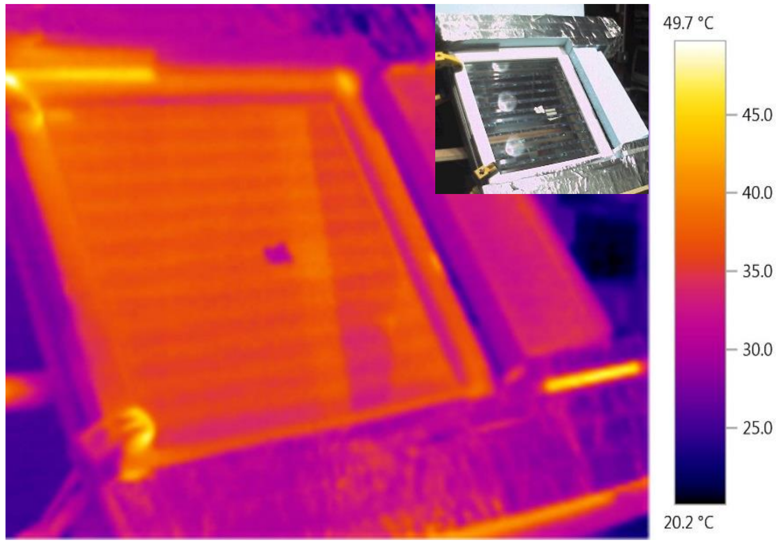


Figure 7. IR image showing temperature distribution on the surface of the CoPVTG prototype with Illumination incident at 20° (data from 15:35: $T_i$=34.3°C, $T_o$=35.7°C and $T_a$=25.7°C).

As demonstrated by the linear regression equations heat loss coefficients ($F_RU_L$) are 27.7 and 25.2 W/m$^2$K and optical efficiencies ($F_R(\tau\alpha)$) 43.8% and 52.6% for the 20° and 55° incidence angles of illumination respectively. The high heat loss coefficients are due to the lack of insulation at the rear of the prototype and the fact that the front of the PVT absorbers conduct heat to the ambient via the concentrating glass lens. The difference of the optical efficiencies for the two incidence angles is the result of the TIR concentrating incident illumination onto the PVT absorbers.

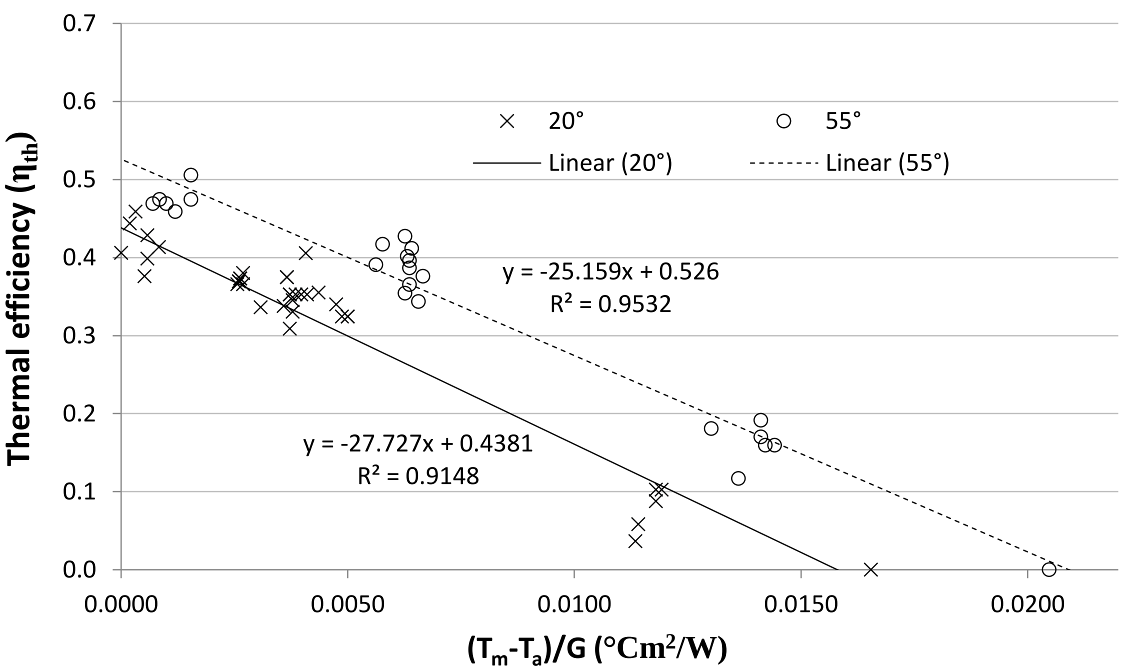


Figure 8. Instantaneous efficiency curves for the thermal efficiency of the CoPVTG prototype at 20° and 55° incidence angles of illumination.

## 6. Conclusions

The CoPVTG prototype was tested with illumination incident at 20° (775 W/$m^2$ intensity) and 55° (503 W/$m^2$ intensity). The two incidence angles are at either side of the 37° critical angle for TIR for which the concentrating lens were designed. Tests showed that TIR at the concentrating glass lens is effective in enabling incident beam radiation to reach the PVT absorbers of the prototype at the higher incidence angle. A 1.56 effective increase in radiation reaching the PVT absorbers was measured.

The CoPVTG prototype can act as a low efficiency solar thermal collector with a zero-loss efficiency which depends on the incidence angle of solar radiation and the effects of TIR. 52.6% and 43.8% maximum efficiencies were measured at 55° and 20° respectively. Due to the lack of effective insulation the thermal performance reduces rapidly for both examined incidence angles of illumination (measured $F_RU_L$ is 25.2 and 27.8 W/$m^2$K at 55° and 20° respectively). The prototype stagnated at 12.9°C and 10.3°C above the ambient temperature at the 20° and 55° incidence angles respectively. Open circuit voltage drops of 6.7% and 4.5% were measured between stagnation and zero-loss temperatures for the 20° and 55° incidence angles respectively The tests results demonstrate the necessity for removing heat from the PV cells and the potential of the technology to be an effective PVT collector.

## Nomenclature

| | |
|---|---|
| $A$ | aperture surface area of the prototype (0.2304 $m^2$) |
| $A_d$ | air duct cross sectional area (0.00504 $m^2$) |
| $c_p$ | specific heat capacity for air (1.005 kJ/kgK) |
| $F_R$ | collector heat removal factor |
| $G$ | illumination intensity (W/$m^2$) |
| $I_{sc}$ | short circuit current (A) |
| $Q$ | thermal power (W) |
| $T_i$ | inlet air temperature (°C) |
| To | outlet air temperature (°C) |
| $T_m$ | mean air temperature (°C) |
| $T_a$ | ambient air temperature (°C) |
| $T_{PV}$ | PV cell temperature (°C) |
| $T_{glass}$ | glass lens temperature (°C) |
| $U_L$ | overall heat loss coefficient (W/$m^2$K) |
| v | air velocity (m/s) |
| $V_{oc}$ | open circuit voltage (V) |

| | |
|---|---|
| $\alpha$ | absorptance |
| $\eta_{th}$ | thermal efficiency of prototype |
| $\rho_{air}$ | density of air (1.205 kg/m$^3$) |
| $\tau$ | transmittance |

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