Solar Energy Tracker 2008

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Abstract:
This paper outlines the concept behind taking the sun's energy, concentrating it and then focussing it in two axes, onto a water cooled target. The steps taken to achieve this tracking control system are discussed, with a brief overview of the electrical and mechanical systems used. Preliminary results are given and a comparison made with results achieved from other more conventional static solar absorbers or collectors. Finally, recommendations are made as to the future use and deployment of the Solar Energy Tracker (SET).

Introduction: Currently in the solar hot water energy market place there are a wide range of different types of solar hot water collectors. For the domestic user these typically range from being as simple as a black plate with a copper pipe on the rear to remove the heat, through to evacuated tubes, and nowadays to evacuated tubes with heat pipes. The breadth of options available to the domestic user further extends to the choice of hot water storage devices and uses, ranging from a simple tank on the roof, through to a separately fed solar input on a hot water cylinder and then on to a completely separate hot water cylinder heat loop or coil. The choice and type of reflectors, and the angle of mounting of the solar collector, all have an important part to play in the efficient operation of a solar hot water collector.

On a larger scale there have been and currently are ongoing attempts to produce large amounts of hot water in excess of 20 deg C from the collector which may then be used for commercial applications and possibly the generation of electricity. These may range from the Heliostat type, where a tower is mounted in the centre of a ring or partial ring of mirrors, which then focus concentrated solar energy onto the tower and create superheated steam either by water cooling the tower or more usually by using oil as the cooling media. This approach needs vast tracts of land though to achieve its end and goals. The other approach is to use a tracking mechanism and track the sun's path across the sky in either one or two axes. This type can be used for either generating hot water or electricity. The latter has become the current trend with a 'Stirling' cycle engine being attached to the focal point of the mirrors.

However, this type is not the only type which can be used, and in 1997 attempts were made by two Queenstown inventors to track the sun in both the X and Y axes, to focus the sun's energy from mirrors onto a target and to use water as the intermediate fluid to cool the target. In 2003, the Solar Energy Tracker (SET) test rig was donated to and acquired by the Christchurch Polytechnic Institute of Technology (CPIT). Since then the SET test rig has been assembled from a kitset of parts, and the original design improved or redesigned as necessary. This has been followed by progressive testing of each subsection and the operation of the complete machine for 2 years, whilst all the time optimising machine performance and safety. One of the goals was to create a temperature rise in excess of 20 deg C across the target for as many conditions as was possible.

This paper reviews the current domestic solar hot water technologies, and presents the findings from 3 to 4 years of research into the solar energy tracker (SET) along with its possible commercialisation. It briefly covers aspects of the mechanical and electrical design, and PLC programming and safety interlocks to prevent the SET from 'strangling itself' or 'cooking itself.' It also covers the mirror substrate testing, and the method of comparing the results as measured and achieved against accepted and published literature, and as compared to other domestic solar thermal hot water systems. The paper concludes with recommendations for the future development and possible commercialisation of the SET.

2.0 History

In 1996 and 1997, Jim Finnie and Dave McLaren, the original inventors of the SET, came up with the concept of tracking the sun in two axes to maximise the solar gain that was available from any given solar radiation. Two axes tracking at that time was somewhat of a novelty, with single axis tracking being relatively common.

The concept of the SET was to track the sun and to reflect and concentrate, by the use of mirrors, the sun's radiation onto a target placed at the focal point of the mirrors, which is cooled by a coolant media passing through it, which in turn heats up. The media can then be used for other processes ranging from space heating, to water heating, through to steam generation.

The coolant media can be gas or liquid, however, in this case it is water. In its original concept, the SET had to be energy self sufficient, in other words it had to generate its own energy, and use its own energy without being a net importer of energy. This meant that the original SET had to contain a lead acid battery (12V DC), and a photo-voltaic (PV) panel complete with battery charging circuit. All the electrics for the panel were therefore constrained to being operated at low voltage DC, namely 12 V DC. The SET was operated in 1997 on this basis, and in 1997 received much media coverage both here and overseas. However, no funding to support the project was forthcoming and so the SET lay idle for a number of years. When it was shipped to Christchurch in 2003, the 75W PV panel and battery had been sold off to recover some of the capital costs. The result of this is that several changes have had to be made to the SET. Currently the SET uses a combination of mains power, and has a mains power derived 24 V DC and a 12 V DC power supply. The intention has been to retain the 'self contained' feature of the original SET as much as possible, with all 12 V DC motors being carried over in the control system redesign. When the SET is fully commercialised it may be offered in two models, one as it is at present, with a mixture of voltages, and the other model as a low voltage (12 V DC) fully self contained system.

3.0 Construction

The SET is comprised of a series of mirrors of two basic sizes, with outside overall dimensions of 3m by 3m or a possible collection area of 9m^2. However, included in the area is a space for a 75W PV panel, the slot for which is currently left empty. The SET pivots in both the X and Y axes and the 13 mirrors are individually adjustable for alignment to the target. The target is water cooled, with water passing through it at a given flow rate.

The redesigned SET features a PLC controller for flexibility, and to allow for easy system function changes, rather than using the original and now unreliable analogue controller. The current SET is seen as a test bed to prove that the concept works and to allow quantification of its performance. When fully commercialised, the self contained model will feature a micro-controller to allow it to operate from a low voltage DC supply.

The complication with two axis tracking is the added mechanical and electrical complexity of having a mounting frame and a pivoting X axis frame onto which a pivoting Y axis frame must be added. The electrical complexity comes about in having to manage two axes, two sets of travel interlocks, and two sets of drive motors.

The SET X axis mounting frame comprises a tripod arrangement onto which the rotating X axis frame mounts, using a truck hub connected to a triangular frame. This moves independently of the tripod, as shown in Figure 3.1. At the apex of the triangle in the bottom left of Figure 3.1 is the battery box (just out of shot), which was used to store a 12 V DC battery, but now acts solely as a counterweight for the X axis with the correct battery weight being in shingle. All the original protection circuitry, fuses, isolators and cabling have been left intact. To this triangular frame are attached two pivots for the Y axis frame to mount onto. The Y axis framework then hinges about these two pivots as shown in the centre of Figure 3.2. A Y axis sub-frame then fits inside the Y axis frame and provides attachment points for the mirrors, as shown in Figure 3.3a.

Figure 3.1. Tripod frame, with X axis support frame mounting

Figure 3.2. X axis sub-frame upright leading to pivot and Y axis frame.

The Y axis contains a boom to which is mounted the target and auto-tracking sensor, as shown in Figure 3.3b. The target is comprised of a series of inverted anodised matt black aluminium (in 'V' section format) as shown in Figure 3.3c.

Figure 3.3 a, b & c. Y axis boom, auto-tracking sensor &boom extension and target.

The inventors had decided to use IR photo-diodes as the basis of the auto-tracking Printed Circuit Board, with a Light Dependent Resistor being used for the daylight sensor and system triggering. The choice of IR photo-diodes was made following several attempts using LDR's, time clocks, and finally using IR photo-diodes to allow them to follow the sunlight and solar radiation under a wider range of weather conditions, including any solar radiation on cloudy days. The IR photo-diodes were mounted on the end of the Y axis boom extension to which the target is attached as shown in Figure 3.3b. At this time there were three IR photo-diodes mounted in series for each of the 4 auto-tracking commands; boom up, boom down, track left, and track right.

The original control system was a combination of relay and analogue controls. In 2003, when the SET concept was still being investigated and researched, this proved to be unreliable and prone to frequent failure. In part, this was due to the use of a 'Krone' panel for all wiring and diode terminations, but the age of many components was also a contributing factor. The original control panel contained relays for the interfaces between circuits; target analogue temperature and no flow PCB; light level PCB; auto-tracking PCB; charging controller; circulation pump motor fault, tray full, no flow and over-pressure PCB's with all wiring being terminated onto the 'Krone' panel, as shown in Figure 3.4 a & b.

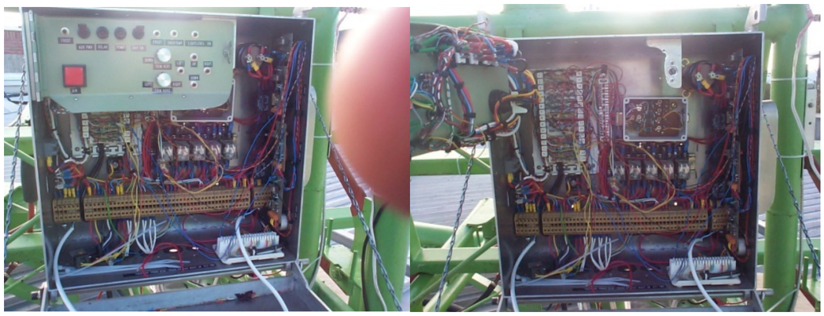

Figure 3.4 a & b. Original control system with and without the front gear-plate.

On the original SET, drive motors were required to drive the axes. The drive axis motors used were small multi-voltage (4.5 to 15V DC) motors which came complete with an offset inline gearbox (148:1 reduction). This was coupled to a final worm drive, which in turn rotates the axis around the chassis via a fixed chain drive, as shown in Figure 3.5. The signal for the drive motors came from the analogue controller and was sent to the drive controller PCB which comprised an underrated H bridge circuit. There was no encoder fitted for position feedback on these motors, instead travel limit switches were used to indicate to the control system the position of the X and Y axes.

Figure 3.5. Y axis DC motor, inline offset gearbox, worm drive and final drive chain obscured at rear.

The circulation pump (CP) used was a small geared offset inline geared DC motor with 100rpm final shaft speed, corresponding to a water flow rate of 4 l/min. This motor and gearbox drive a peristaltic pump (as shown in Figure 3.6), which is ideally suited for this environment as it offers a high efficiency and low loss in pumping.

Figure 3.6. DC geared motor for CP, with peristaltic pump head assembly.

The other core of the SET is the mirrors which focus the solar radiation onto the target. These were fabricated out of an aluminium sheet which was formed to provide a slight curvature to more sharply focus the solar radiation. These are secured to the Y axis sub-frame via a ball joint on the mirror's rear, clamping to a V notch clamp bar which then is secured to the Y axis sub-frame. A 3M mirror substrate is applied to the target side of the aluminium plate, to ensure good reflectivity of the solar radiation to the target, as shown in Figure 3.7 a & b.

Figure 3.7 a & b. The mirrors and mirror curvature.

4.0 The SET at CPIT.

4.1 Mechanical analysis

Before any re-assembly of the complete SET from the kit parts delivered to CPIT in 2003 was undertaken, a mechanical engineers report on the structural strength of the SET was commissioned. This report identified four possible areas of failure, mostly pertaining to the size and type of bolts holding the mirrors onto the Y axis sub-frame; the size and type of bolts securing the Y axis sub-frame onto the Y axis frame; the buckling of the boom lattice under a severe storm force wind gust (which was deemed acceptable); and finally the buckling of Y axis pivot points, as shown in Figure 4.1a. To solve this issue a bottom gusset was welded on, as shown in Figure 4.1b.

Figure 4.1a & b. The Y axis pivot point before (a) and after (b) the addition of a gusset.

In late 2003, the assembly of the SET with three mirrors was completed and testing showed up a number of mechanical issues (mirrors mounted incorrectly, Y axis sub-frame alignment, travel limit switches placement, to name a few). Several electrical issues were also encountered, not the least of which are the need for updating the analogue control system with a PLC, improving the daylight and auto-tracking sensors and their interaction with the control system, the addition and correct interlocking of park limit switches as well as travel limit switches, and circulation pump no flow, tray sensor, over-pressure and motor fault interlocks. All of these were progressively resolved in 2004, 2005 and the early part of 2006.

4.2 Control System

The new control system is based around the Omron CPM2A PLC (Programmable Logic Controller) platform, with the PLC programme being broken into several subroutines or sections, with each section dealing with a separate area of the SET's overall operation. For example, the issues pertaining to the auto-tracking and daylight controls of the SET form two sections of the PLC programme. Other areas include start up, water pump controls, analogue temperature sensing and controls, alarms, compressor controls (used for frost), park position control, and real time start-up and shut down controls.

The PLC code also contains a number of other features including: the ability to park the SET in either of two positions, one facing NW with the other more common position facing SE: is fully interlocked with all the travel limit switches and park limit switches; allowing for full manual and automatic control of the SET; features self resetting non critical alarms; has remote status indication; allows automatic shutdown and morning restart; and performs a combination of shut down and stayput, and shut down and park manoeuvres based on alarm condition and light levels. The SET has been operating on a largely continuous basis, (except for extreme weather events, when it is manually shutdown), since May 2006 and was only stopped in late December 2007 for Christmas vacation.

4.3 Auto-tracking and daylight controls

After considering other options, such as LDR's, time based and GPS based controllers, the decision to replace the IR photo-diodes with more current models was undertaken and applied successfully to the operation of the SET in late 2004. The auto-tracking sensor and circuit now comprises one IR photo-diode for each axis, with the daylight controls being derived from a centrally mounted IR photo-diode. All daylight and auto-tracking sensors feed to a revised light and auto-tracking control circuit which in turn outputs a direction signal and a sufficient light signal to the PLC. The PLC, providing all the necessary interlocks are satisfied, will send an auto-tracking direction output signal to one of 4 relays which control the direction of the drive motors, i.e. auto-track sensor and circuit required to track left, then fed to the PLC which then feeds to the track left relay, which then applies power to the drive motor to make the SET track left. Figure 4.2 shows the revised control system cabinet with PLC, relays and operator controls.


Figure 4.2. The revised SET control panel

4.4 Mirror and mirror substrate testing

In 2003, attempts were made to ascertain the best type of mirror substrate and to procure additional quantities. However, although the type of mirror substrate was traced to being a 3M product, 3M had ceased manufacturing it. Two alternatives were then sourced, one from Clear Dome Solar Flex, (an offshoot company from the NASA space programme) and the other from Nielsen Enterprises. Samples were procured from each company and placed, along with a piece of 3M substrate, onto 5 specially fabricated aluminium panels and left to weather in a combination of environments. In these tests, with up to 4 test sites were used, which included 2 panels being sent to Antarctica, one for the summer season and the other for 12 months. All the 5 test panels have had their substrates monitored and photographed monthly, and have remained un-cleaned except for some spot cleaning in January 2008. It would appear the Clear Dome Solar Flex substrate as used by NASA to reflect heat energy away from the shuttle is not really suitable for the SET as it has poor surface reflectivity and is more designed to prevent heat energy from entering the skin of the shuttle, rather than reflecting solar radiation. The Nielsen substrate, in the size and type purchased by CPIT in 2003, has shown signs of promise, and does appear to be suitable. However, by January 2008, it was beginning to show signs of minor surface deterioration (minor silver tarnishing) due to a cracked top Mylar layer. Further testing of this substrate is recommended before any deployment of this substrate to the Mark 2 version of the SET. It should be noted that the mirror substrate currently on the SET is the 3M substrate which has received damage from a cover sheet mounted in front of it after the foam insulation layer was removed by a student in2004. .

4.5 SCADA recording system

A SCADA (Supervisory Control And Data Acquisition) system has been installed and commissioned to record the inlet and outlet temperatures of each of the solar thermal devices, as well as the flow rates, ambient air temperature, and solar radiation activity as measured by a fixed and tracking pyranometer.

4.6 The BET at CPIT

Christchurch Polytechnic Institute of Technology offers a 3 year Engineering Technology degree, and as part of a student's final year of studies the student is expected to undertake a major project. Two project students were involved in helping to set-up and establish the SET at CPIT, one from each of the years 2003 and 2004. In 2005, 6 and 7 other sponsors and solar thermal hot water research and development have been performed to ascertain how effective the SET's performance is against other solar thermal hot water systems.

This is with both older and more modern solar thermal technologies incorporated into their design. The basis of comparison between the SET and the other solar thermal systems on test at CPIT is that all the systems are exposed to the same environmental conditions.

5.0 Results

In 2005 CPIT installed and commissioned a solar hot water thermal system, which was a 20 tube evacuated tube heat pipe system and came with a controller and circulation pump.

Following on from this in 2006 and 2007, CPIT was contacted by three solar thermal companies to carry out performance testing, as well as research and development, of their solar thermal panels. All of this research is covered by confidentiality agreements; however, CPIT has on test a combination of flat plate, finned flat plate (a copper pipe with fins attached), evacuated tube thermosyphon batch, evacuated tube heat pipe continuous flow (in two sizes) and finned tube heat pipe in an evacuated tube continuous flow system, currently under research and development on the roof of C block. In August and December of 2007, further systems were added in the form of three types of airwalls, where air is used as the cooling media rather than water. Detailed results from this research and development testing are not as yet available.

However, in general terms: a more conventional flat plate collector has a temperature gain at the collector in direct sunlight of between 8 to 10 deg C; a finned flat plate under the same conditions has a temperature gain of up to 12 deg C, but more usually averages 11 deg C; an evacuated tube heat pipe has a temperature gain under the same conditions of between 14 to 16 degrees, and a finned evacuated tube type has a temperature gain of up to 18 deg C. The SET under these conditions, with a dirty and scratched mirror substrate, has a temperature gain averaging 11 to 13 deg C. Following a light polishing of the mirror substrate, the temperature gain from the SET was of the order of 22 to 25 deg C. The polishing compound life expectancy is short lived and wears off with rain and moisture in 6 to 8 weeks depending on the weather conditions.

6.0 Discussion

The SET and its control system have proven to be reliable with no major safety concerns in the time it has been in operation at CPIT.

From the observations and the early analysis of the results for the SET, it can be seen that temperature gains in excess of 20 deg C is possible with a flow rate of 4 l/min through the target. Both Masters[1] and Quaschning[2] indicate that when a temperature rise of 20 deg C or more is readily achievable from a concentrating collector, then the energy levels are such as to warrant further investigation, processing and the use additional add on processing or generating plants. Possible uses for this hot water energy range from space heating applications at the low end, to complex power plants using steam turbines for electricity generation at the high end. Figure 6.1 shows the SET in operation with polished mirror substrate in fine weather in 2007. Mother Earth News[3] also believes in an article published in their December 07/January 08 issue that the way forward (to, at least in part solving the global energy shortage) is to use concentrating solar power and in particular parabolic mirrors to focus the sun's energy.

Figure 6.1. The revised SET with polished mirror substrate in operation in 2007.

7.0 Recommendations for future

For the future deployment of the SET, it is planned to build a Mark 2 version based more around the outer shell casing shape of a satellite dish, to further investigate and possibly use the Nielsen Enterprise Mylar as a coating for the satellite dish and its application to a curved surface, to further investigate a larger area and other means of achieving a higher concentration of solar energy onto the target and to try to improve the SET system still further with a higher temperature gain at the target and with a view to trying to making better use of the temperature gain that is possible with this system.

8.0 Conclusion

This paper has shown the history surrounding the development behind the SET, its re-deployment, redesign and final commissioning at CPIT. Preliminary results obtained from up to 24 months of continuous testing indicate encouraging temperature and energy gains have been obtained when compared to other solar thermal hot water systems. The results prove the original inventor's concept was correct and the idea of concentrating the sun's energy has merit and is worthy of further investigation despite all the problems so far and yet to be encountered with the Mark 2 version.

9.0 References

[1] Gilbert M. Masters, "Renewable and Efficient Electric Power Systems", Wiley, New Jersey, 2004.

[2] Volker Quaschning, "Understanding Renewable Energy Systems", Earthscan, London, 2006.

[3] Mother Earth News, December 2007/January 2008, 'Why Solar Power is Our Best Solution', Page 8, Issue 225, ISSN 0027-1535.