

# THERMAL ANALYSIS OF PARABOLIC TROUGH SOLAR COLLECTORS FOR ELECTRIC POWER GENERATION

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## Abstract

The performance of parabolic trough solar collectors solar thermal electric generation systems is evaluated for Australian climate conditions. The largest Solar Electric Generation System (SEGS) currently in operation uses a parabolic trough solar collector and synthetic oil in the collector loop. To improve performance and reduce costs, future designs propose direct steam generation in the collector. In this study parabolic trough collectors are analysed for operation with; Synthetic oil (currently used in LUZ plant) and water (future proposal). Working fluid phase change in the collector is considered and an efficiency equation for the trough collectors is developed. A simulation model linked with the TRNSYS simulation program is used to determine the annual performance of a typical trough configuration under Australian conditions.

## INTRODUCTION

The parabolic trough evacuated tube solar collector is one of the main technologies currently used in the solar electric power generation (SEGS) plants. The performance of these plants can be predicted if the optical thermal losses from the collector are known. The collector thermal loss can be evaluated by solving the governing equations for heat transfer or from an empirical investigation. Little work has been published on the thermal characteristics of evacuated tube absorber for trough collectors. Most of the studies are on the commercial trough collector used in the southern California solar electric power generation system (SEGS) at Kramer Junction. The receiver of the SEGS system consists of a steel heat absorption pipe coated initially with black chrome and later with a cermet selective surface of low thermal emittance, Cohen (1993), Cohen & Kearney (1994). The pipe is surrounded by an evacuated glass tube with anti-reflection coatings on both surfaces. The collector heat transfer fluid used in the SEGS plants is Therminol VP-1.

An optical model of a parabolic trough collector has been developed by Heinzl et al, (1995). The effect of the change of absorber tube temperature on absorber emissivity in the LUZ systems was reported in, Lippke (1996). The increase of emissivity with temperature has a major effect on collector thermal loss and collector efficiency.

A direct steam generation collector (DSG) has also been proposed as a future generation of the LUZ type trough collector, Cohen & Kearney (1994). This configuration has the

advantage of eliminating the costly synthetic oil, intermediate heat transport piping loop and oil to stream heat exchanger.

To model the performance of a SEGS plant, the collector efficiency must be defined in terms of the various thermal loss paths. In this work a detailed analysis of the thermal performance of the LS2 trough collector is carried out. A collector efficiency equation is developed in terms of absorber wall temperature by computing radiation and convection losses and using test data for the LS2 collector to determine conduction losses through residual gas and the end bellows. The model was then applied to Australian weather data to determine the annual performance.

## LUZ COLLECTOR THERMAL LOSS TEST

As part of a program to investigate ways to reduce operating and maintenance costs for SEGS system, Sandia National Laboratories and KJC operating company made a large series of tests of the LS2/LS3 collectors, Cohen (1993). Tests were conducted on a tracking platform using heat collection elements (HCE) with cermet coating. The optical efficiency was determined to be 73.1%.

The heat loss tests were repeated with HCE lost vacuum and again with broken glass in order to evaluate the impact of failure of tubes on the performance of the solar field. The collector thermal loss with respect to the synthetic oil working fluid temperature is shown in figure 1. The tests show the effect of the vacuum space between the steel tube and the glass tube on the reduction of the total thermal loss.

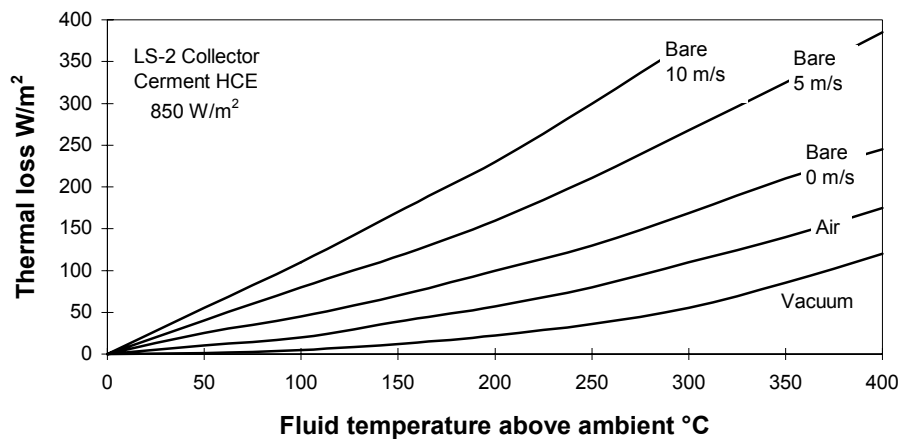


Fig 1. Collector thermal losses for vacuum, lost vacuum (Air), and broken glass (Bare) HCE (Cohen, 1993).

## THERMAL ANALYSIS OF TROUGH COLLECTOR

The LUZ trough collector receiver tube consists of absorber elements (steel tube surrounded by evacuated glass tube) joined together at each end by metallic bellows. The fluid used in the collector is Therminol VP-1 oil. There are many problems

associated with the use of synthetic oils at high temperatures some of these are; flammability, toxicological effect, thermal stability and high cost, Guyer (1989). To overcome these problems the next generation of LUZ collector is proposed to be direct steam generation with the collector directly heating the power plant feed water. To develop a collector efficiency equation for the new collector, the LS2 thermal test results on the oil type collector must be converted to the DSG collector design by allowing for the change of working fluid properties for the collector specification shown in table 1.

Table 1. LUZ Collector specifications

Collector area m <sup>2</sup>	Absorber length m	Optical efficiency %	Absorber tube inner diameter m	Absorber tube outer diameter m	Absorber thermal conductivity W/m <sup>2</sup> K	Glass tube diameter m	Glass tube emissivity
547	99	73.1	0.059	0.07	54	0.1	0.9

The variation of emissivity of the absorber with wall temperature was measured by (Lippke, 1996) and (Cohen, 1993) for black chrome and cermet selective coatings. The absorber wall emissivity ( $\epsilon_{ab}$ ) can be related to absorber wall temperature ( $T_{wall}$ , °K) as follows:

$$\epsilon_{ab} = 0.00031 \cdot T_{wall} - 0.0216 \quad (1)$$

The thermal analysis is based on a combination of the collector thermal loss from radiation, convection and conduction. The main thermal loss from the absorber tube outer wall to the evacuated glass tube (surrounding the absorber) occurs by radiation. The heat loss from the glass cover tube occurs by radiation to the sky and by convection to the surrounding air by wind or natural convection. The second part of the loss from the collector takes place between the absorber tube and the ambient via the vacuum bellows and supports. To establish an expression for overall heat loss from the absorber the heat balance between the absorber tube and the evacuated glass tube must be considered,  $ql_{(ab-g)} = ql_{(g-a)}$ . Where,  $ql_{(ab-g)}$  is heat loss by radiation between the absorber tube and the evacuated glass tube (the convection loss in this region is zero due to the vacuum) and  $ql_{(g-a)}$  is the heat loss by radiation and convection from the glass tube outer surface. The heat loss determined from the above heat balance can be fitted to the following approximate function for the purpose of determining collector efficiency;

$$ql = (a + c \cdot V_{wind}) \cdot (T_{ab} - T_a) + \epsilon_{ab} \cdot b \cdot (T_{ab}^4 - T_{sky}^4) \quad (2)$$

where  $a$ ,  $b$  and  $c$  are convection, radiation and wind factors.  $V_{wind}$  is wind speed in m/s,  $T_{ab}$  is absorber outer wall temperature in °K and  $T_a$  is ambient temperature in °K.

The sky temperature ( $T_{sky}$ ) can be related to dry bulb temperature and dew point ambient temperature as follows (Martin and Berdahl, 1984);

$$T_{sky} = (\epsilon_{sky})^{0.25} \cdot T_a \quad (3)$$

where,  $\epsilon_{sky} = 0.711 + 0.56 (t_{dp}/100) + 0.73 (t_{dp} / 100)^2$  (4)  
and,  $t_{dp}$  is dew point temperature in °C.

The computed thermal loss from the heat balance model does not include the end bellows and residual gas conduction loss. A comparison with the LUZ collector experimental heat loss measurements shown in figure 2 give an indication of these conduction losses. The conduction losses shown in figure 2 were fitted to equation 2 to determine the conduction heat loss as a function of  $(T_{ab} - T_a)$ .

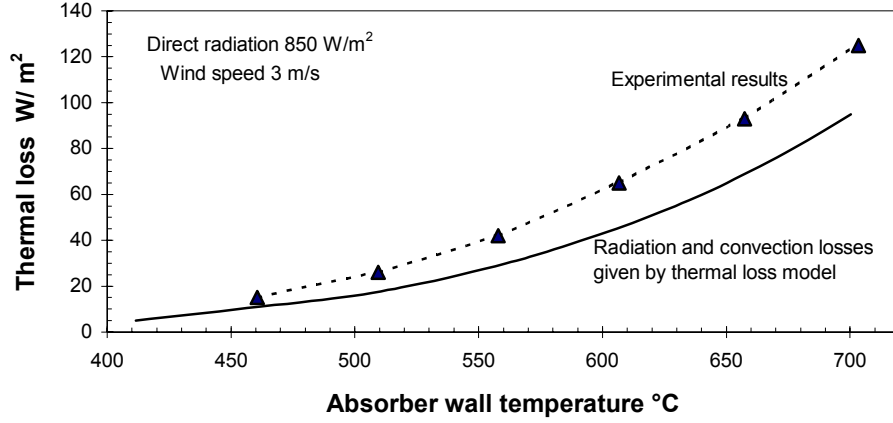


Fig 2. Measured and computed collector thermal loss.

The factor (a) in equation 2 can be developed to include both convection and conduction losses. The a, b and c coefficients determined by least squares fitting of the measured heat loss are;

a= 0.0498 (computed by adding conduction loss to the heat balance model), b =2.14  $\times 10^{-9}$ , c = 0.0018 (computed from the heat balance model).

Equation 2 can be used to predict the thermal loss of the collector for any working fluid if the fluid properties and phase state are known.

The efficiency of the collector ( $\eta$ ) can be expressed in terms of the thermal loss (equation 2) and the collector optical loss ( $\eta_{opt}$ ) as follows;

$$\eta = \eta_{opt} \cdot K_{\tau\alpha} - (a + c \cdot V_{wind}) \cdot \frac{(T_{ab} - T_a)}{I_{direct}} - \epsilon_{ab} \cdot b \cdot \frac{(T_{ab}^4 - T_{sky}^4)}{I_{direct}} \quad (5)$$

where,  $I_{direct}$  is the direct solar radiation and  $K_{\tau\alpha}$  is the incident angle modifier.

The incident angle modifier accounts for non-normal incident effects that cause reflected rays to be scattered or to miss the absorber tube. The incident angle modifier data was developed from the analysis of Heinzl et al, (1995) which describes the  $K_{\tau\alpha}$  factor of the LS2 collector in terms of beam radiation incident angle. Equation 5 is expressed in terms of  $T_{ab}$  rather the conventional  $T_{in}$  or  $T_{bulk}$  so that it can be used in the three different phase regions independently of the fluid and phase condition. The absorber temperature is calculated in terms of the fluid temperature and internal film coefficient for the appropriate flow condition.

For water as the working fluid in the collector, the thermal analysis must be divided into three regions due to phase changes. The heat transfer coefficient for the single phase water and dry steam regions can be calculated by using water and steam properties to evaluate the Reynolds number, Prandtl number and then Nusselt number. To find the heat transfer coefficient in the two phase zone the type of flow pattern must be determined. Two main patterns are required to be checked; stratified flow and annular flow. In stratified flow the Shah correlation can be used, and the Chan procedure for annular flow, Stephan, (1992). To calculate the efficiency of the DSG collector the absorber wall temperature is evaluated in each phase region from the thermal balance between absorbed radiation, heat loss and useful heat gain. By applying equation 5 in each phase section the efficiency of that section can be evaluated. Then the overall collector efficiency evaluated by determining the extent of each phase region.

## PRESSURE DROP IN THE DSG TROUGH COLLECTOR

The SEGS power plant collector field consists of many solar collector assembly units each working independently to generate the required energy output and connected in parallel with the other assemblies. The length of an assembly depends on the type of the collector used which governs the number of assemblies in the field. The total pressure drop in such a power plant depends on the size of each assembly unit. The flow rate in a DSG collector is small to enable the collector output to reach the required steam condition in a single pass. In the water and steam regions, the pressure drop correlation for single phase flow can be used. The pressure drop of two phase flow in a DSG collector can be calculated using the Martinelli and Nelson method for high pressure steam flow in pipes, Stephan, (1992). The pressure drop in the LUZ DSG collector in the three phase regions is shown in figure 3. This figure also shows the pressure drop for the higher flow rate single phase oil system as used in the current LUZ plant. The pressure drop when using synthetic oil at the highest temperature (oil flow rate  $< 0.55$  kg/s) is almost equal to the pressure drop in the DSG system when dry steam is generated at the collector exit (water flow rate  $< 0.15$  kg/s).

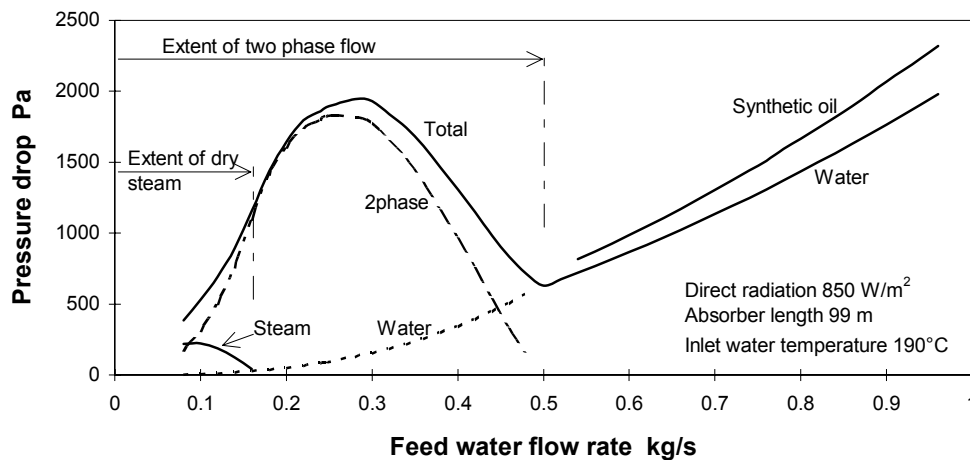


Fig 3. Total pressure drop in the LUZ, LS2 collector for water and oil working fluids.

## DISCUSSION

The collector thermal loss and the semi empirical efficiency equations (2 & 5) describe the collector performance. This is shown in figure 4 as a comparison between experimental and analytical results of the thermal loss for different collector fluid temperatures. The measured and computed values are very close in the temperature range between 250- 400 °C (at wind speed 3 m/s) which covers the operation range of a typical power plant. The efficiency in the different phase regions of a direct steam generation collector is a function of radiation level as shown in figure 5. The efficiency

of the water and two phase sections increases with increasing direct radiation due to the increase of heat transfer coefficient with increasing bulk temperature. Contrary to this, the dry steam region efficiency decreases with increasing direct radiation due to fluid property changes at high temperature causing a decrease of heat transfer coefficient with temperature. Thus the overall collector efficiency increases with increasing radiation up to 600 W/m<sup>2</sup> for the flow used (when dry steam generation starts), then decreases as the dry steam region grows with higher radiation levels.

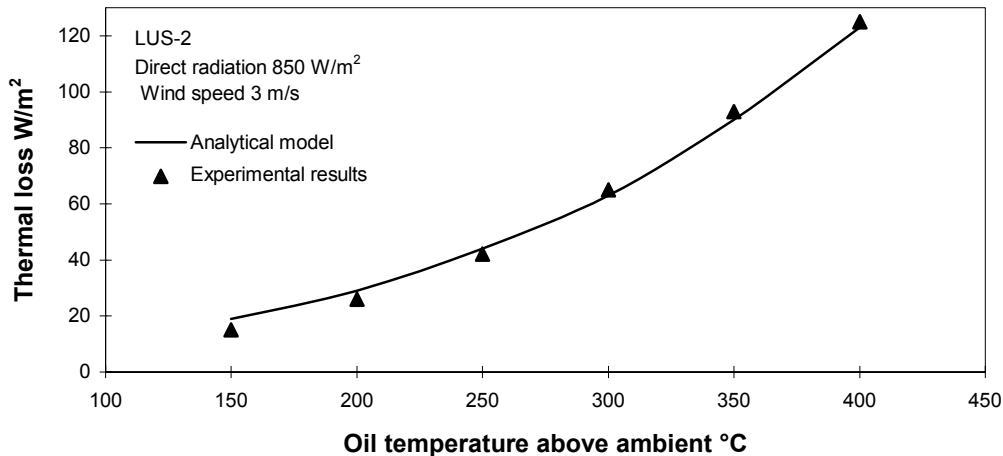


Fig 4. Experimental and analytical thermal loss of the LUZ LS2 collector

The collector efficiency equation was used to compute the annual performance of LUZ (DSG) trough collector at different Australian sites (Alice Springs, Darwin and Longreach). The North - South collector axis orientation was used for these sites and the irradiation model of Perez was used to compute beam radiation. The collector performance model described in this paper was linked with the TRNSYS simulation program and an hour by hour simulation of the energy gained by the collector was determined using the radiation data for these sites, Morrison and Litvak, (1988). A simulation using the same model was also carried out using TMY2 weather data for Daggett California (Daggett is close to the site of two of the LUZ SEGS plants), Marion and Urban, (1995). The annual energy gained by the collector at the Australian sites is close to the collector output at Daggett as shown in figure 6. The difference in the time of minimum and maximum values of the collector output at Daggett and the Australian sites is due to the site locations being in different

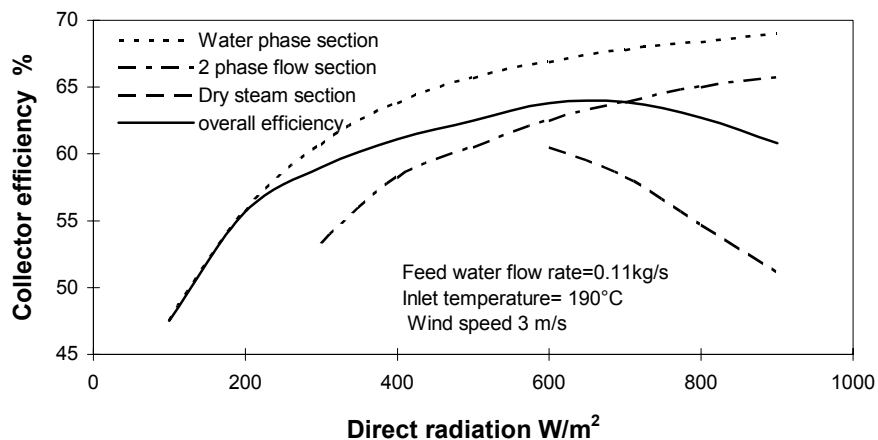


Fig 5. Direct steam generating collector efficiency

hemispheres. As the site latitude decreases the solar incident angle decreases and thus the incident angle effect becomes smaller. This makes the collector output at a site like Darwin (or any other location near the equator) almost steady throughout the year.

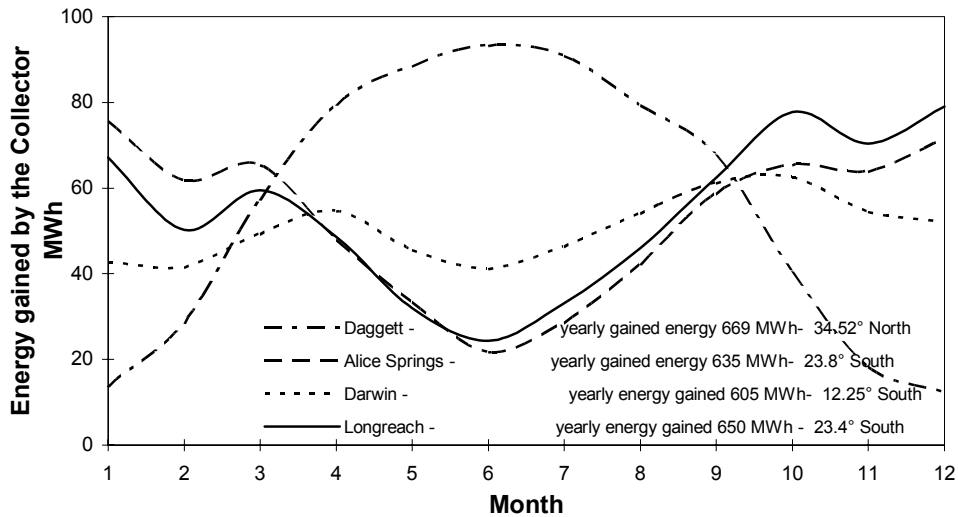


Fig.6. DSG collector thermal output at different Australian sites and LUZ plant site (Array area = 547 m<sup>2</sup>).

## CONCLUSION

The largest solar electric power plant, currently in operation, is the SEGS (LUZ parabolic trough collector). The thermal cycle uses a heat transfer fluid (synthetic oil) to transfer energy from the collector field to a Rankine steam cycle via a heat exchanger. As a future development for this type of plant, steam would be generated directly in the solar field to reduce capital and operating costs.

Thermal losses of the LUZ trough collector were described in terms of absorber emissivity, wind speed, absorber temperature and ambient temperature. A semi empirical equation was developed to predict the efficiency of the parabolic trough collector in terms of absorber wall temperature so that it can be used with any working fluid. The collector thermal loss when using synthetic oil as the working fluid was found to be higher than in the DSG collector. The direct steam generation collector efficiency has a maximum value when the dry steam generation region starts.

The pressure drop analysis shows that the pumping power required for the DSG collector is similar to the pumping power for the existing collector (using oil).

A simulation model based on the TRNSYS package was developed to simulate the annual performance of the collector. The direct steam generation trough collector at Australian locations has a yearly thermal output close to the collector (modified for steam generation) at the SEGS power plants at Daggett California. The monthly average collector output at Darwin is almost steady during the year at approximately 605 MWh, output for inland Australian sites are higher but have a pronounced seasonal variation.

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