Comparative Efficiency Study of a Solar Trough Receiver: Hot mirror and selective coating

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Abstract. We consider a solar trough system in which cylindrical parabolic mirrors focus the sun's radiation onto a receiver pipe, heating it. Conventionally, the pipe is enclosed in a glass cover under vacuum and the dominant radiation losses are reduced by the use of a selective coating on the receiver pipe. We study the suitability of applying a 'hot mirror' coating on the inside of glass cover instead, which transmits in the visible but reflects well in the infra-red. We compare the performance of the 'hot mirror' coating using its optical properties (reflectivity, absorptance and emissivity). It is seen that a hot mirror is a viable alternative, and certainly allows higher temperatures of the working fluid and therefore higher Carnot efficiency.

1. Introduction

The solar trough is among the most-studied solar systems. The largest solar trough power plant in the world, the SEGS (Solar Energy Generating Systems) in California with a peak capacity of 364 MW, has been operational and studied in detail since the mid-eighties [1]. Such systems consist of long, cylindrical trough-shaped parabolic mirrors which concentrate the sun's radiation on the focal line where the receiver unit (collector tube) runs and through which a 'working fluid' circulates and is heated [1, 2] (figure 1). The working fluid is then circulated to a power station where it is converted to electricity. Generally, the receiver unit must be designed in such way that it loses as little heat as possible via radiation, convection and conduction to its surroundings [1]. The receiver consists typically of a glass cover, encapsulating a metal receiver pipe with a vacuum in between. The vacuum minimizes convective losses from the heated receiver pipe to the surroundings [1, 3]. Conduction losses are reduced by minimizing the contact between the receiver pipe and the glass sleeve [4]. Thermal radiation losses are reduced by the use of a selective coating applied to the receiver pipe [5, 6]. The research has been done on different aspect of the receiver unit [3, 7]. Our research concentrates on the possibility of a substitute for the selective coating and the improvements of selective coating absorptance, emissivity and long-term stability in air.

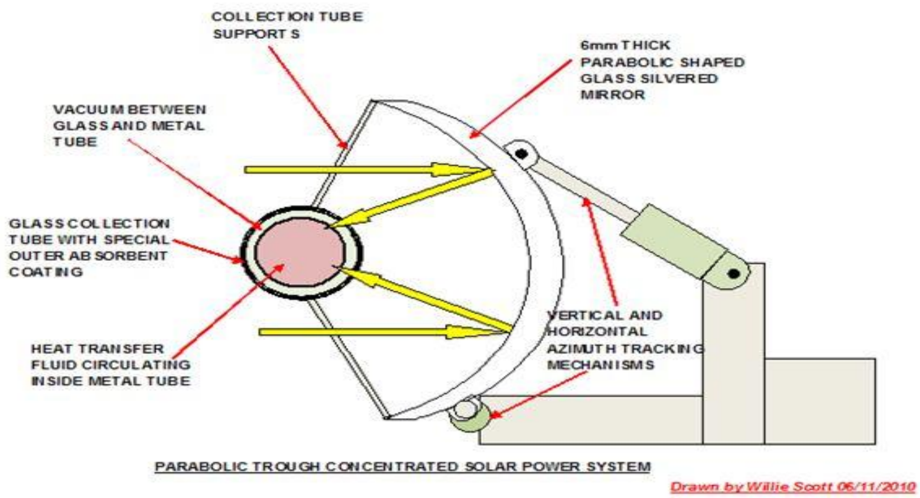

Figure 1: Solar Trough Plant layout: http://japanesestyletattoos.blogspot.com/2011/05/solar-power-plant-layout.html

2. Selective Coating

The selective coating (i.e. Black Chrome) is a dielectric material which absorbs well in the visible region of spectrum (i.e. sunlight) but emits very poorly in the Infra-Red region [3], which is the radiation that is lost from the receiver . A selective coating on the receiver pipe will render the system more efficient in terms of the fraction of solar energy absorbed (i.e. α=0.94) by the working fluid, heating it.

Numerous works have been published on selective coatings on the receiver pipes and their properties [1, 2, 3]. This research into selective coatings, we want to create a stable (long-term stability in air), efficient coating over a wide temperature range (0°C to 1000°C) which has the high absorptance and emissivity in Infrared region.

The main weakness of commercial selective coatings is that they will deteriorate thermally at temperatures around 680°K (~400°C) [2, 5, 6, 9, 10], thereby restricting the maximum temperature to which the receiver pipe can be heated, and hence the Carnot or Rankine efficiency of the subsequent heat to electrical conversion [11]. The temperature of the receiver pipe rises with its length, hence the receiver pipe length is restricted to a maximum length, after which thermal breakdown of the selective coating occurs.

The basic idea in this paper is to investigate the theoretical performance of an alternative to selective coating, the “hot mirror”.

3. Hot mirror

A hot mirror (i.e. ITO) refers to a dielectric coating that is designed to reflect the IR region of the spectrum and to transmit the visible. In our model, it is applied to the inside of the glass cover. The hot mirror on the glass cover will reflect IR radiation emitted from the receiver pipe back onto itself, thereby reducing the amount of thermal radiation leaving the receiver unit [3]. The net effect is similar to that of the selective coating. The hot mirror coating also breaks down thermally around 680K [4]. The hot mirror is applied to the glass cover, which is cooler than the receiver pipe during operation (by around 400K). It is therefore possible to sustain higher temperatures in the receiver pipe using a hot mirror instead of a selective coating on the receiver pipe. This additional temperature increase is transferred to the working fluid, and subsequently to the steam power station, where it will improve thermal efficiency [5].

The questions posed in this paper are, first, how a hot mirror system compares to a selective coating system in terms of efficiency of heat transfer into the working fluid; and second, whether a hot mirror system can be used in a temperature region where the selective coating system breaks down (>680K) on the receiver pipe. In order for the plant to continue operating beyond the breakdown length of the selective coating, we suggest that, in this high temperature region of the receiver pipe, the selective coating can be substituted by a hot mirror coating on the glass cover (hybrid system).

4. Receiver unit analysis

By using heat transfer mechanism and conservation of energy law we derive the equation of the receiver pipe and the glass cover [3]. To our best knowledge, the receiver unit has not been studied in this context. We could also find no reference to the possibility of a hybrid system, where different types of technologies are used at different temperature ranges, within this context, as in this paper. Our model describes the heat transfers via radiation between the glass cover, the receiver pipe and the outside, as well as the conductive heat transfer into the working fluid and convective losses to the surroundings. The relevant equations are presented in the following section.

4.1. Heat transfer mechanism

Radiation falling on a surface interacts with it via the mechanisms of reflection (r), transmission (t) and absorption (a = 1 – r – t) in relative proportion [2, 3, 9,] where, "r" and "t" are the reflection and transmission coefficients respectively. In each case, the superscript refers to whether the term of interest applies to visible (v) or Infrared (IR) and the subscript refers to its physical location, being either on the glass cover (g) or the receiver pipe (r).

We did not specifically consider convection and conduction interactions inside the receiver unit, since they are sub-leading mechanisms of heat transfer at high temperatures and can also be assumed to remain similar in both systems. And during our calculations we use some approximations [3]. The heating of the receiver unit was assumed uniform. We do not take a temperature gradient along the circumference of the glass cover or receiver pipe into account. This amounts to assuming good heat conduction of the materials involved. We assumed the glass cover and the receiver to be close enough together so that the majority of the radiation leaving either one is intercepted by the other [3]. We also do not include any heat transfer effects into the working fluid due to the type of flow it displays, laminar or turbulent. We also did not include the abovementioned sub- leading heat transfer mechanisms, such as convection and conduction inside the receiver. Considering all above approximations we get the following equations [3]:

Equations for glass cover [3]:

$$AQ^v + BA_r\mathcal{E}_r\sigma T_r^4 + CA_g\mathcal{E}_g\sigma T_g^4 - hvA_g\left(T_g - T_0\right) = 0 \quad (4.1)$$

Equation for Receiver [3]:

$$DQ^v + EA_r\mathcal{E}_r\sigma T_r^4 + FA_g\mathcal{E}_g\sigma T_g^4 - \frac{KA_r}{L\left(1+\frac{KA_rK1}{L}\right)}(T_r - T_L) = 0 \quad (4.2)$$

Where A, B, C, D, E and F are in terms of transmission and reflection coefficients [3].

The last terms in both equations represents heat loss via convection to the surrounding by the glass cover (4.1), and heat loss to the working fluid via conduction (4.2). Both depend on the local temperature difference linearly. These results have been tested in numerous limits of coefficients and provided the expected results argued on purely physical grounds

4.2 Computer simulation

We have written a program which simulates the behavior of a solar trough system [3]. Solar radiation is incident on a section of the receiver unit, where it undergoes the interactions described above leading to equations (4.1) and (4.2). The program solves these equations simultaneously for the equilibrium temperature of the glass cover and receiver pipe based on the optical properties of the coating [3]. We used five different thicknesses of ITO coatings, whose coefficients are provided in table 1.

Reflectivity	Transmissivity	Absorptance
0.75	0.0585	0.191
0.80	0.0464	0.153
0.85	0.351	0.115
0.90	0.0234	0.0766
0.95	0.0117	0.03833

Table1: Reflectivity (R), Transmissivity (T) and Absorptance (A) for five different hot mirror coatings

Quantities derived from the program include the equilibrium temperatures of the glass cover, the receiver pipe and the working fluid at incremental points along its length, as well as all heat flows related to them. We used a visual basic program coupled with an excel worksheet. We further checked the results against an independent program in Math CAD.

5. Results and Discussion

5.1 Results

Figure 2 shows the results for the temperatures of glass cover and the receiver pipe for the hot mirror system as a function of length of the solar trough system. Results for the of heat transfer into the working fluid for the hot mirror system are shown in figure 3.

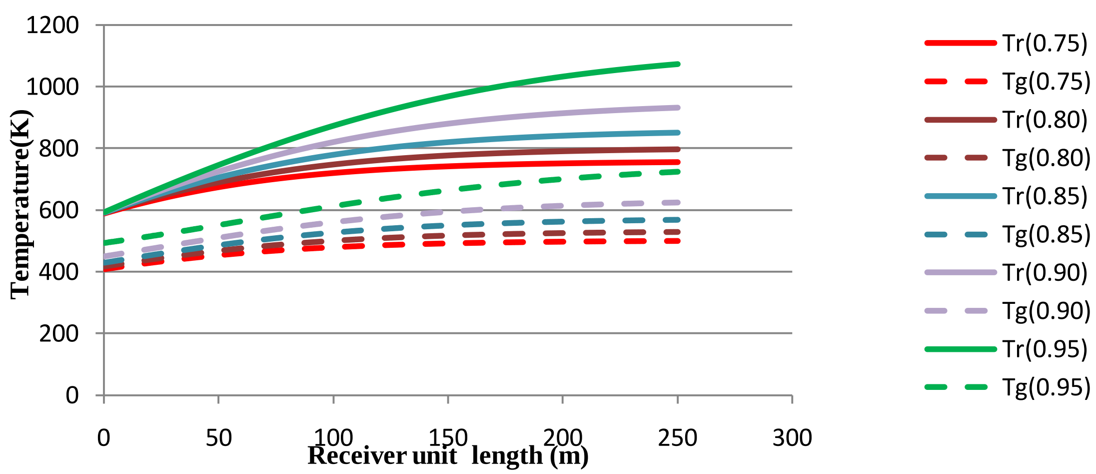

Figure 2: Comparison of the temperatures of glass cover and the receiver pipe for hot mirror system as a function of length of the solar trough system. Figures are labeled by their IR reflectivity.

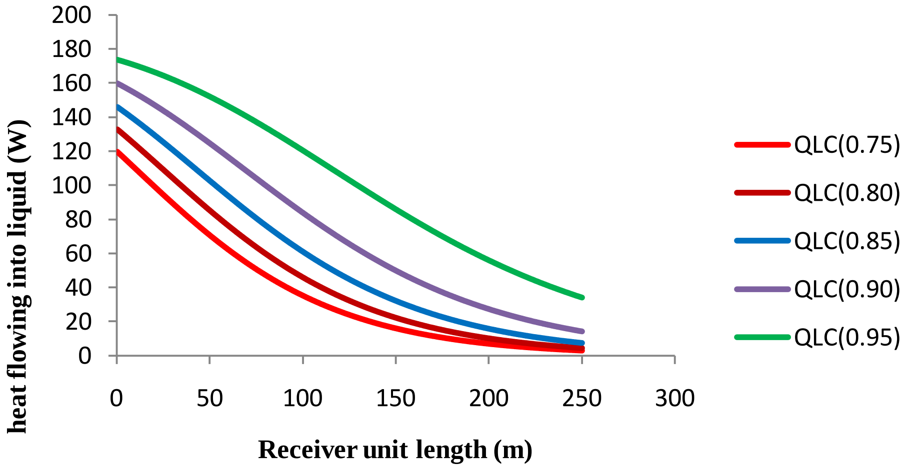

Figure 3: The heat going into the working fluid for hot mirror as a function of receiver unit length.

5.2 Discussion

The simulation was started at a temperature close to where failure of the selective coating is expected (600K). Relative equilibrium temperatures of hot mirror can be compared in this region, and the question of applicability answered.

The selective coating should be used to the temperatures where it is stable (below 680K). After this critical temperature, a substitution to the hot mirror system is advisable.

The glass cover temperature is seen to be much lower than the receiver pipe temperature (by 200K), and this allows the glass cover to be coated with a hot mirror, since the hot mirror coating can operate at these temperatures. This will allow the working fluid to be heated to more elevated temperatures, making the overall system more efficient. The hot mirror coating is stable up to temperatures of about 600K, and the glass cover temperatures exceeds this for Tglass (R=0.95) and Tglass (R=0.90).

Figure 3 indicates the heat moving into the working fluid (heat into working fluid, QLC) along the pipe unit length. It is seen that the hot mirror perform significantly better in terms of working fluid heat transfer for higher reflectivity in the IR region, which increases the efficiency of a solar trough plant.

6. Conclusions

A set of heat transfer equations was derived, modeling the thermal behavior of a solar trough receiver unit. Radiative heat transfer within the receiver unit was considered, as well as convective losses to the outside, and heat transfer into the liquid. A code was written using the equations, and this was the main source of our results. It was seen that the glass cover temperature was sufficiently low for a hot mirror system for some reflectivities. This allows the construction of solar trough systems with longer receiver pipes of two types: selective coating should be used in the temperature region where it is appropriate, and a hot mirror system at higher temperatures. This will allow the working fluid to reach a greater temperature, and hence better overall plant performance. For this purpose, it would be well worth investigating the hot mirror receiver system in the future.

We compared five different thicknesses of ITO coating with different optical properties. It was seen that the heat transfer was higher for higher IR reflectivity of the hot mirror, and that more heat was transferred into the working fluid. However, very high reflectivities can lead to the temperature of the glass cover to exceed the working temperature of the hot mirror coating, damaging it.

References

[1] Sargent and Lundy (2003). *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts,* Subcontractor Report, SL-5641, prepared for the U.S. Department of Energy and National Renewable Energy Laboratory, Chicago, Ill

[2] Twidell J. and Weir T. (2006). *Renewable Energy Resources*, pp. 115-145, pp. 146-176. Taylor & Francis Group, New York.

[3] Cyulinyana MC. (2011). Investigation into applicability of existing renewable energy technologies and possible efficiency increase, case study: Rwanda, pp.85-122. M.Sc. thesis, University of the Witwatersrand, South Africa.

[4] DURAN. Tubing, Capillary and Rod of Borosilicate Glass3.3, Schott, Glass made of Ideas. Online at: http://www.schott.com/tubing/english/download/schott-tubing_brochure_duran_english.pdf

[5] Kennedy C. E. and Price H. (2005). Progress in development of high-temperature solar-selective coatings. NREL/CP-520-36997 Proc. ISEC2005 2005 International Solar Energy Conference August 6-12, 2005, Orlando, Florida USA, ISEC2005-76039

[6] Kennedy C.E. (2002). *Review of Mid- to High-Temperature solar Selective Absorber Materials.* NREL/TP-520-31267, Golden, CO: National Renewable Energy Laboratory

[7] Kaltschimitt M, Streicher W. and Wiese A. (2007). *Renewable energy technology- economics and environment*, Springer, Berlin, New York.

[8] Academic press. (2009). *Renewable Energy Focus handbook*, Elsevier.

[9] Kreith F. and Kreider J.K. (1978). *Principles of solar engineering*, pp. 1-33, pp. 85-159, pp. 203-309. Hemisphere Publishing Cooperation.

[10] You Y. and Hu E.J. (2002). A medium-temperature solar thermal power system and its efficiency optimization. *Appl. Thermal Eng.* **22**, 357-364.

[11] Ferrer P. (2008). Enhanced efficiency of a parabolic solar trough system through use of secondary radiation concentrator, *S. Afr. J. Sci.* **104**.

[12] Kumashiro Y. (2000). *Electric Refractory Materials,* Marcel Dekker Inc., New York