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Solar selective coating optimization for direct steam generation parabolic trough designs

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Abstract

Solar selective coatings that absorb solar incident light but that inhibit emission of thermal light can have a dramatic impact on the performance of Direct Steam Generation (DSG) systems. In prior art, perfect coatings with instantaneous transitions between high absorption and low absorption have been modeled. In this paper non-ideal spectral, environmental, and material properties of solar selective coatings are shown to have significant effects on the efficiencies and optimum transition wavelengths of real systems. By introducing more real world parameters into the coating optimization it is desired that a more cost effective and efficient system can be built. It is shown that using ideal conditions the optimum transition wavelength for a DSG system is 1.4 μm with an efficiency of 55.7%. Whereas for a realistic non-ideal DSG system the optimum transition is at 3.4 μm resulting in an efficiency around 30% depending on the concentration factor used. It is then shown that an optimized selective coating will be outperformed by a simple non-selective black absorber with 95% absorption at concentration factors above 80 and above 130 when the AM1.5 spectrum is used.

Keywords: Parabolic trough; Direct steam generation; Solar selective coating

1. Introduction

Direct steam generation (DSG) parabolic trough power plants operate by heating a closed loop of water and steam with terrestrial solar radiation and converting the heated steam to electricity, usually with a steam turbine (Benz et al., 2006; Eck, 2001; Giostri et al., 2012; Mills, 2004; Odeh et al., 1998; Zarza et al., 2006, 2002). In the simplest system the water is heated, evaporated, and then sent to a steam turbine where the energy is converted to electricity. The steam is then condensed to water and pressurized, so that it is ready to undergo the process again (Benz et al., 2006; Eck, 2001; Giostri et al., 2012; Mills, 2004; Odeh et al., 1998; Zarza et al., 2006, 2002). The solar heater in a DSG will consist of multiple parts: water heater, evaporator, and steam super-heater. Only in the evaporation stage is the water/steam at a single temperature throughout the stage, and thus this is the only stage where a single optical coating placed on the surface of the steam pipe will be optimal for collecting solar light and minimizing emissive heat loss. The other stages should have coatings that vary based on the temperature of the water/steam being heated to be optimal (Chester et al., 2011; Olson and Talghader, 2012; Schmidt and Park, 1965; Sergeant et al., 2009).

An optimum solar selective coating is one that absorbs the maximum amount of incoming solar radiation and emits the minimum amount of thermal radiation. These coatings are possible because all objects, above 0 K, emit thermal radiation that obeys Planck's law of thermal

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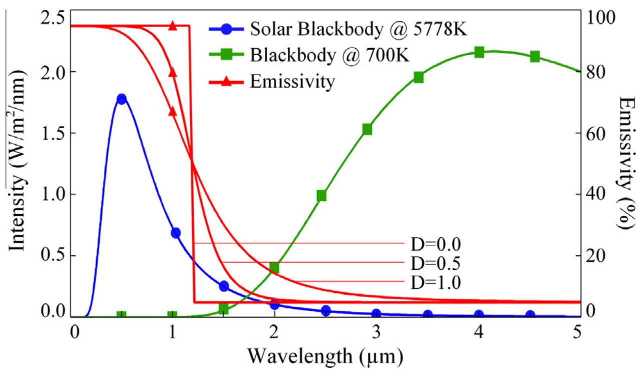

Fig. 1. Incoming solar and the thermal blackbody radiation emission spectrums. The sun has an effective emission temperature of 5778 K, yet the peak intensity is comparable to the intensity at the surface of a 700 K blackbody because of the great distance between the earth and sun. The emissivity curve was calculated with $\alpha = .95$, $\varepsilon = .05$, $D = 0$, 0.5, and 1 decade with $\lambda_s = 1.2$ μm.

emission Eq. (1) which has the property that the emission peak intensity of hot objects is at shorter wavelengths than colder objects for blackbodies where the emissivity is unity. Because the sun is much hotter than the DSG system and the solar intensity peak is at much shorter wavelengths, an emissivity curve can be imagined which has a large solar absorption but low thermal emission as seen in Fig. 1. The transition between absorption and reflection has been optimized in prior research for systems at a single temperature with ideal, 100% solar absorbing and 0% infrared (IR) emission properties (Schmidt and Park, 1965; Sergeant et al., 2009). It has also been shown how to take into account the non-ideal, less than 100% absorption and reflection, and solar concentration factor to find the optimum transition wavelength (Olson and Talghader, 2012).

$$u_\lambda^{\text{device}}(T) = \frac{2hc^2}{\lambda^5}\frac{1}{[\exp(hc/\lambda k_B T) - 1]}\varepsilon(\lambda) \quad (1)$$

Eq. (1) describes the thermal radiation spectral power density for any device, in this case the DSG system, where h is Planck's constant, c is the speed of light, λ is the wavelength, k_B is Boltzmann's constant, and T is the temperature of the blackbody. Also $\varepsilon(\lambda)$ is the wavelength dependent emissivity, where $0 \leqslant \varepsilon(\lambda) \leqslant 1$, and is equal to 1 for a blackbody. To find the radiation flux at a distance from the source, Planck's law is modified by a ratio of surface areas, assuming thermal radiation obeys an inverse square law. To find the incoming solar irradiance at the surface of the earth the ratio is r^2/R^2, where r is 6.96×10^5 km as the sun's radius, and R is 1.496×10^8 km as earth's orbital radius (Williams, 2013).

$$u_\lambda^{\text{solar}}(T) = \frac{2hc^2}{\lambda^5}\frac{1}{[\exp(hc/\lambda k_B T) - 1]}\varepsilon(\lambda)\frac{r^2}{R^2} \quad (2)$$

A solar selective coating has a high absorption in the visible but a high reflectivity in the infrared. Ideally, this transition from 100% absorption to 0% absorption would occur as a step function. A non-ideal step would lose some solar radiation and emit extra IR radiation.

2. Absorption to reflection transitions

To take a non-ideal step function into account, the emissivity of a selective coating can be represented as in Eq. (3). The following equation was found empirically to fit some selective coatings fabricated and measured in the past (Olson and Talghader, 2012; Schmidt and Park, 1965; Sergeant et al., 2009) and is not meant as a fit for all possible solar selective coatings.

$$\varepsilon(\lambda) = \frac{\alpha - \varepsilon}{1 + \left(\frac{\lambda}{\lambda_s}\right)^{\left(\frac{4}{10^{D/5} - 10^{-D/5}}\right)}} + \varepsilon \quad (3)$$

In Eq. (3) α is the emissivity in visible spectrum, ε is the emissivity in the IR, and D is the transition length in decades of wavelength, and λ_s is the transition wavelength. The factor D will have a large effect on the efficiency of the system as will be shown later. To illustrate a typical selective coating design, Fig. 1 shows the incoming solar radiation, device blackbody radiation at 700 K, and the emissivity of a non-ideal selective coating.

From Fig. 1 and noting that from Kirchhoff's Law the thermal emissivity has to be equal to the absorptivity, it can be seen that much of the solar spectrum can be absorbed while the thermal emission from the selective coating is limited. The optimum transition wavelength of a selective coating can be solved for by equalizing the incoming and outgoing thermal radiation through a process of integrating Eqs. (1) and (2) over the entire spectrum, for many device temperatures and transition wavelengths, and finding where the two integrals equate (Olson and Talghader, 2012). This type of optimization has been done in the past (Olson and Talghader, 2012; Schmidt and Park, 1965; Sergeant et al., 2009) with the exception of the effect of the transition length D which can be seen in Fig. 2. The transition length does not affect the optimum transition wavelength significantly but it does noticeably lower the equilibrium temperature which will have a greater effect

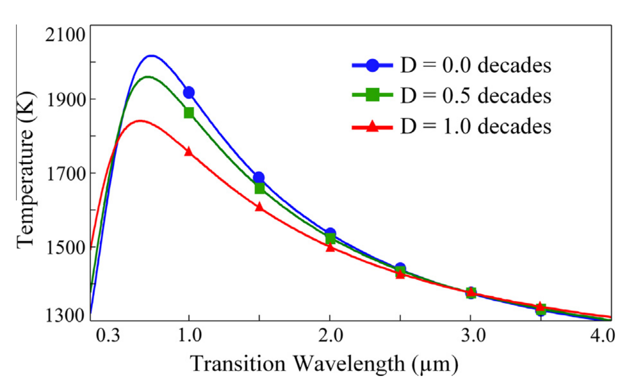

Fig. 2. Effect of the transition length, D, on the optimum transition wavelength, λ_s. The curve was calculated for an emissivity of $\alpha = .95$, $\varepsilon = .05$, and solar concentration equal to 80.