

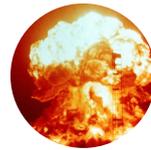
The heat transfer and thermodynamic performance of a parabolic trough receiver with perforated plate inserts

Aggrey Mwesigye, Prof Tunde Bello-Ochende and Prof Josua Meyer

Parabolic trough solar collectors are one of the most technically and commercially developed of the available concentrated solar power technologies. The parabolic trough's linear receiver is a central component to the performance of the entire collector system. Its state and design greatly affect the performance of the entire collector system.

The receiver's performance is significantly affected by the thermal loss and heat transfer from the absorber tube to the working (heat transfer) fluid. The conventional receiver consists of an evacuated glass envelope to minimise the convection heat loss and a selectively coated absorber tube to minimise the radiation heat loss. Numerous studies have been carried out to characterise the thermal performance of the receiver and to determine the thermal loss at different receiver conditions (Burkholder and Kutscher, 2008; Burkholder and Kutscher, 2009; Lüpfert, Riffelmann, Price, Burkholder and Moss, 2008; Dudley, Kolb, Mahoney, Mancini, Sloan and Kearney, 1994; Dudley, Evans and Mathews, 1995; Padilla, Demirkaya, Goswami, Stefanakos and Rahman, 2011). From these studies, it has been shown that receiver thermal loss depends largely on the state of the annulus space between the glass cover and the absorber tube itself, its selective coating and temperature, the wind speed and the heat transfer from the absorber tube to the heat transfer fluid.

The presence of circumferential temperature gradients in the receiver's absorber tube is a major concern.



The researchers considered a simplified model of the parabolic trough receiver.

At low flow rates, higher temperature gradients in the tube's circumference can cause bending of the tube so that the glass cover will eventually break (Almanza, Lentz and Jiménez, 1998; Muñoz and Abánades, 2011). The peak temperature in the absorber tube facilitates degradation of the heat transfer fluid, as these temperatures increase above 673.15 Kelvin (K) (Moens and Blake, 2010; Li, Wang, Lei and Li, 2012). The degradation of the heat transfer fluid results in hydrogen permeation in the receiver's annulus. With formation of hydrogen in the receiver's annulus, its thermal loss increases significantly, which affects the collector's thermal performance (Forristall, 2003).

Most failures of parabolic trough receivers, especially the breakage of the glass cover, have been attributed to the circumferential temperature gradients in the absorber tube. Therefore, reducing these temperature gradients and temperature peaks can increase the life span of the receiver and prevent thermal loss due to vacuum loss and hydrogen permeation in the receiver's annulus space. The maximum temperature gradient for the safe operation of receiver tubes is about 50 K (Wang, Liu and Xu, 2013).

The enhancement of convective heat transfer in the receiver's absorber tube is one of the relevant solutions to the above concerns. With improved convective heat transfer in the absorber tube, circumferential temperature gradients and peak temperatures in the absorber tube can be reduced and risks of breakage and hydrogen formation can be minimised. As such, heat transfer enhancement in the receiver's absorber tube has received considerable attention in the recent past. Ravi Kumar and Reddy (2008) numerically analysed a receiver with various porous fin geometries and compared its performance to that of a receiver with longitudinal fins.

Ravi Kumar and Reddy (2009) also investigated the performance of the receiver with a porous disc at different angles of orientation, different heights and different distances between the consecutive discs.

Muñoz and Abánades (2011) analysed an internally helically finned absorber tube with a view to improving thermal performance and minimising the temperature gradients in the absorber tube. The absorber tube temperature difference was reduced by between 15.3 and 40.9%.

All these studies used an approximate heat flux boundary condition on the receiver's absorber tube. The use of a realistic non-uniform heat flux boundary condition is crucial in determining the temperature gradients, peak temperatures and entropy generation rates in the receiver.

Recently, Cheng, He and Cui (2012) analysed the heat transfer enhancement of a parabolic trough receiver using unilateral longitudinal vortex generators with a realistic non-uniform heat flux boundary condition. The wall temperatures and thermal loss were found to decrease with each geometrical parameter considered. Wang et al. (2013) investigated heat transfer enhancement using metal foams in a parabolic trough receiver for direct steam generation using realistic non-uniform heat flux boundary conditions. The maximum circumferential temperature difference was shown to drop by 45%.

Only a few investigations have been made of the effect of heat transfer enhancement on the thermodynamic performance of enhanced devices. Therefore, in this research study, a numerical investigation was carried out of the heat transfer, fluid friction and thermodynamic performance of a receiver with centrally placed perforated plates. The plates were centrally placed to provide heat transfer enhancement in the core flow, thereby avoiding any possible hot spots that can facilitate the degradation of the heat transfer fluid, which are characteristic of heat transfer enhancement methods with recirculation, separation and re-attachment. In addition to heat transfer performance, using the entropy generation minimisation method, the effect of heat transfer enhancement on the thermodynamic performance of the receiver is also investigated and presented. This study presents an investigation of the thermal and thermodynamic performance of a receiver for a parabolic trough solar collector with perforated plate inserts.

The perforated plate assembly is considered to be supported on a thin, axially placed rod as shown in Figure 1(a). The placement of the perforated plate is defined by the spacing between the two consecutive plates (ρ), the diameter of the plate (d) and the angle of orientation measured from the positive y-axis (β). β is negative in the clockwise direction and positive in the anti-clockwise direction.

In their analysis, the researchers considered a simplified model of the parabolic trough receiver in which the effect of the central rod and other supports is considered negligible. Further still, the flow was found to be periodically fully developed after about five perforated plate inserts, regardless of the spacing. Therefore, for this analysis, a periodic module of the receiver's absorber tube was considered, as shown in Figure 1(c).

Similar to actual receivers, the space between the absorber tube and the glass cover is considered evacuated to very low vacuum pressures (0.013 Pa) so that only radiation heat loss takes place. The receiver tube that was used is similar to the SEGS LS-2 receiver.

The receiver parameters used are shown in Table 1. Due to the symmetrical nature of the model, only half of the receiver tube was considered in this analysis. The parameters used in this study for the reflector, receiver and perforated plate inserts are given in Table 1.

Governing equations

For the range of Reynolds numbers considered, the flow is in the fully developed turbulent regime. As such, the governing equations used in this analysis for steady-state and three-dimensional turbulent flow are the continuity, momentum and energy equations given.

The study aimed to investigate the thermal, fluid friction and thermodynamic

→ Table 1: Geometrical and optical values of the parabolic trough collector

	Reflector		Receiver		Perforated plate
a_c	6.0 m	d_{ri}	0.066 m	β	-30–30°
L_c	7.8 m	d_{ro}	0.07 m	d	0.03–0.06 m
ρ	0.96	τ_g	0.97	p	0.04–0.20 m
σ_c	0.0002mrad	α_{abs}	0.96		

→ Equations

Continuity

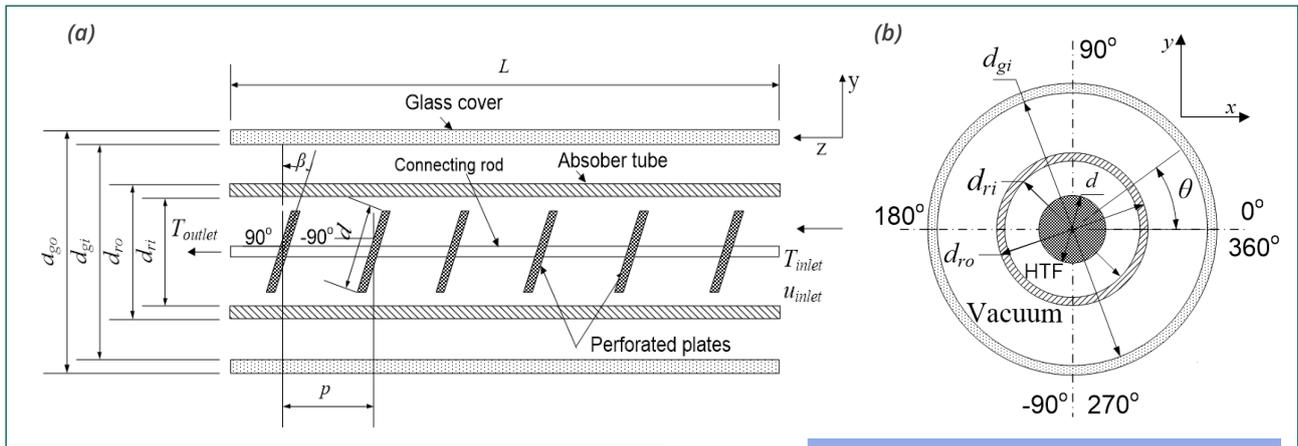
$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

Momentum equation

$$\frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij} - \rho u_i u_j' \right] + S_{ij} \quad (2)$$

Energy equation

$$\frac{\partial}{\partial x_j}(\rho u_j c_p T) = \frac{\partial}{\partial x_j} \left[\lambda \frac{\partial T}{\partial x_j} + \frac{\mu_{eff}}{\sigma_{k,s}} \frac{\partial(c_p T)}{\partial x_j} \right] + u_j \frac{\partial P}{\partial x_j} + \left[\mu_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij} - \rho u_i u_j' \right] \frac{\partial u_i}{\partial x_j} \quad (3)$$



→ Figure 1: Physical model of the parabolic trough receiver with perforated plate inserts: (a) 2D longitudinal section; (b) 2D cross-section view; (c) 3D periodic computational domain.

performance of a parabolic trough receiver with centrally placed perforated plate inserts.

From the study, the Nusselt number and friction factor strongly depend on the spacing and size of the insert, as well as flow Reynolds number. For the range of Reynolds numbers, temperatures and geometrical parameters considered, the Nusselt number increases about 8 to 133.5% with friction factor penalties in the range of 1.40 to 95 times compared to a receiver with a plain absorber tube, while the thermal enhancement factors are in the range of 0.44 to 1.05%.

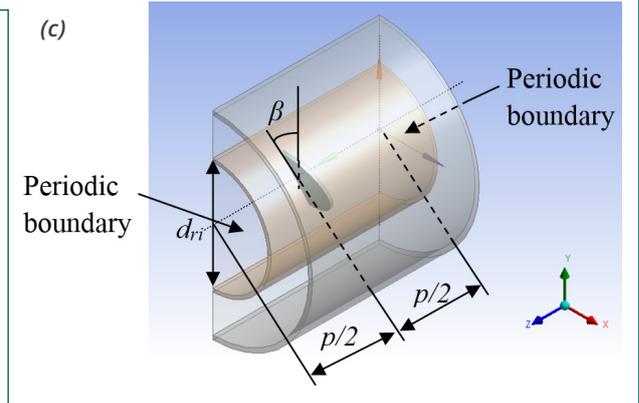
The use of thermal enhancement factors for performance evaluation was shown to be unsuitable for the evaluation of the enhanced parabolic trough receivers.

It does not consider the increase in performance from reduced receiver losses due to lower emissivity and lower absorber tube temperatures. The modified thermal efficiency

of the collector is a more suitable performance evaluation tool because it considers the actual gain in receiver performance and the corresponding increase in pumping power.

The use of perforated plate inserts is shown to increase the modified thermal efficiency of the receiver in the range 1.2 to 8%, depending on the insert spacing, insert size and Reynolds number. The modified thermal efficiency increases in the range of 3 to 8% for insert spacing ranging from $0.08 \leq \tilde{p} \leq 0.20$ and insert size in the range $0.45 \leq \tilde{d} \leq 0.61$ for flow rates lower than 37 m^3 per hour at all inlet temperatures. This flow rate corresponds to the following mass flow rates evaluated at different temperatures: 8.61 kg/s at 400 K, 7.66 kg/s at 500 K, 6.56 kg/s at 600 K and 5.92 kg/s at 650 K.

Significant reductions in absorber tube temperature gradients and peak temperatures were achieved. The maximum reduction in absorber tube temperature gradients was about 67%.



Aggrey Mwesigye is a PhD student in the Department of Mechanical and Aeronautical Engineering at the University of Pretoria. He is specifically interested in the combined use of computational fluid dynamics and optimisation tools for the design of thermal systems.



Prof Tunde Bello-Ochende is an Associate Professor of Mechanical Engineering at the University of Cape Town. His research interests include theoretical, experimental and numerical optimisation of heat transfer devices from macro to micro scales.



Prof Josua Meyer is Head of the Department of Mechanical and Aeronautical Engineering at the University of Pretoria. He is also the Chairperson of the School of Engineering and is an NRF-rated researcher.



→ Techniques to maximise the utilisation of solar power are essential to curb the energy crisis.

As far as safety of the tube is concerned, the reduction in the absorber tube's temperature gradients is beneficial for applications requiring low flow rates where temperature gradients are higher than 50 K.

A reduction in absorber tube temperatures also plays a significant role in reducing radiation losses. Thus, reducing temperature gradients to values lower than 50 K will further improve the performance of the receiver, provided the gained performance is not less than the increase in pumping power.

The use of inserts is also shown to improve the thermodynamic performance of the receiver by minimising the entropy generation rates below a

given flow rate. Overall, volumetric flow rates lower than 43.4 m³ per hour were found to give entropy generation rates lower than those of a receiver with a plain absorber tube for all perforated plate geometrical parameters and temperatures considered.

The maximum reduction in the entropy generation rate was about 52.7%. 🌟

References

Almanza, R, Lentz, A and Jiménez, G. 1998. Receiver behavior in direct steam generation with parabolic troughs. *Solar Energy*, 61:275–8.

Burkholder, F and Kutscher, C. 2008. Heat-loss testing of Solel's UVAC3 parabolic trough receiver. *NREL; NREL/TP*, 550(42394):1–19.

Burkholder, F and Kutscher, C. 2009. Heat loss testing of Schott's 2008 PTR70 parabolic trough receiver. *NREL; NREL/TP*, 550(45633):1–58.

Cheng, ZD, He, YL and Cui, FQ. 2012. Numerical study of heat transfer enhancement by unilateral longitudinal vortex generators inside parabolic trough solar receivers. *International Journal of Heat Mass Transfer*, 55:5631–41.

Dudley, EV, Kolb, JG, Mahoney, AR, Mancini, TR, Sloan, M and Kearney, D. 1994. Test results: SEGS LS-2 solar collector. Sandia National Laboratory: SAND, 94-1884.

Dudley, EV, Evans, RL and Mathews, WC. 1995. Test results: industrial solar technology parabolic trough solar collector. Sandia National Laboratory: SAND, 94-1117.

Forristall, R. 2003. Heat transfer analysis and modeling of a parabolic trough solar receiver implemented in Engineering Equation solver. NREL October: NREL/TP-550-34169:1–145.

Li, J, Wang, Z, Lei, D and Li, J. 2012. Hydrogen permeation model of parabolic trough receiver tube. *Solar Energy*, 86:1187–96.

Lüpfer, E, Riffelmann, K, Price, H, Burkholder, F and Moss, T. 2008. Experimental analysis of overall thermal properties of parabolic trough receivers. *Journal of Solar Energy Engineering*, 130:021007.

Moens, L and Blake, DM. 2010. Mechanism of hydrogen formation in solar parabolic trough receivers. *Journal of Solar Energy Engineering*, ASME:132:031006.

Muñoz, J and Abánades, A. 2011. Analysis of internal helically finned tubes for parabolic trough design by CFD tools. *Applied Energy*, 88:4139–49.

Padilla, RV, Demirkaya, G, Goswami, DY, Stefanakos, E and Rahman, MM. 2011. Heat transfer analysis of parabolic trough solar receiver. *Applied Energy*, 88:5097–110.

Ravi Kumar, K and Reddy, KS. 2009. Thermal analysis of solar parabolic trough with porous disc receiver. *Applied Energy*, 86:1804–12.

Ravi Kumar, K and Reddy KS. 2008. Numerical investigation of energy-efficient receiver for solar parabolic trough concentrator. *Heat Transfer Engineering*, 29:961–72.

Wang, P, Liu, DY and Xu, C. 2013. Numerical study of heat transfer enhancement in the receiver tube of direct steam generation with parabolic trough by inserting metal foams. *Applied Energy*, 102:449–60.