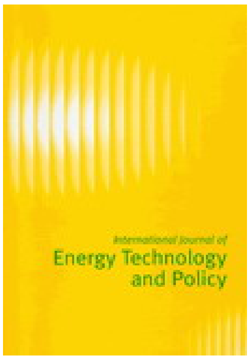

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Development and validation of a thermal model for line focus solar concentrators in water heating applications

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Abstract: Solar concentrators are used to collect solar energy and convert it to heat. Line focus solar collectors operate on the principle of line focus technology where sun radiations are directed to form a line over the receiver. In this paper, thermal model of line focus collectors is developed for the application of water heating. Thermal performance parameters like useful heat flux, heat loss, water exit temperature and thermal efficiency are analysed for different solar radiations and mass flow rates. The model is validated using experimental data from a cooling plant in Seville, Spain. The results of the simulation show good agreement with the experimental data. This thermal model has been used to assess the thermal performance of the collector for the climatic conditions of Ankleshwar, Gujarat, India. The average useful heat flux, the temperature difference of water, and thermal efficiency are reported as 0.656 kW/m^2, 17.64°C, and 76.10% respectively.

Keywords: line focus; solar collector; solar energy; thermal model; water heating.

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1 Introduction

Solar energy is one of the eminent renewable energies that can be used in plenty of applications including industrial process work (Esen, 2004; Esen and Esen, 2005; Esen and Yuksel, 2013). From an Indian standpoint, there is a great opportunity for low-cost solar water heating systems. Solar concentrators can instantly meet the needs for hot water in the industrial sector. This system can be used to heat boiler feed water, washing operations, and other steam producing applications (Sagade and Shinde, 2012). To accomplish this, a variety of solar collectors such as a parabolic trough collector, a Linear Fresnel collector, a parabolic dish, and a solar power tower are employed (Sharma et al., 2017). Solar concentrators use either line focus or point focus technology. Parabolic trough collectors and linear Fresnel collectors are the example of line focus technology (Suman et al., 2015).

Only a few reviews describe the developed model for characterising the performance of line focus technology (Yılmaz et al., 2018). Little attention has been paid to study that summarises the detailed study of techniques used to investigate the performance of the solar technologies. In the early 90s, modelling approaches took place to develop concentric solar power technologies (Duffie and Beckman, 2013; Dudley et al., 1994). These models were developed to serve the purpose of solar plant operation and performance evaluation of parabolic trough collectors (Behar et al., 2013; Fernández-García et al., 2010). Usually, there are three models (Amine et al., 2019) that are used to investigate the entire performance of solar collectors as shown in Table 1.

Figure 1 Thermal models classifications (see online version for colours)

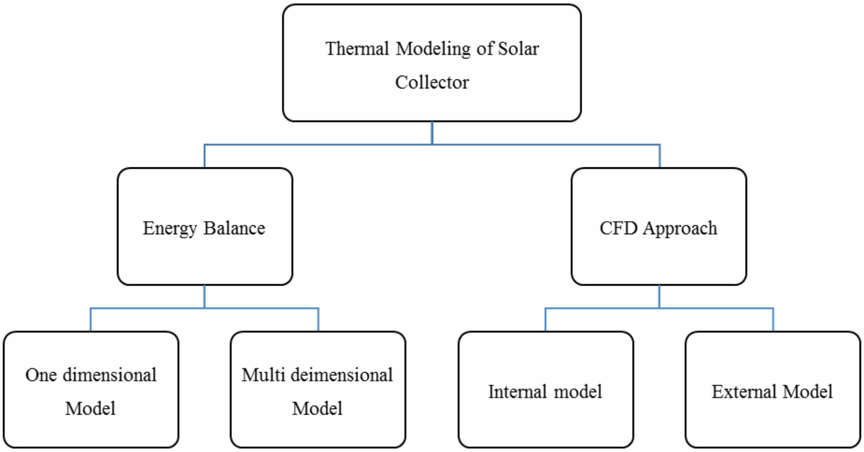


Figure 1 shows the classification of the thermal models that are used for analysis of concentric solar technologies. It is necessary to develop the thermal models to simulate and predict the thermal behavior of concentrators. Literature shows two main approaches i.e., energy balance approach and CFD approach. The former approach is widely used to know the thermal losses and variation of temperature without involving fluid dynamics while later approach emphasise on insight of fluid flow phenomenon (Forristall, 2003; Clausing, 1981; Guangjie et al., 2010; Rodríguez-Sánchez et al., 2014). A number of analytical models are available with the purpose of estimating the exit temperature and thermal loss across the receiver (Vouros et al., 2020). Energy balance models use either a one-dimensional model or multidimensional model. Uniform heat flux is the assumption of one-dimensional model whereas multidimensional models consider the non-uniform heat flux across the receiver. CFD approach modelling is the advanced numerical technique that uses the Navier-Stokes and energy equations to reveal detailed information on heat transfer and fluid mechanics. A mathematical model using Python is presented to test different performance parameters such as loss coefficient, energy gain, collector efficiency, etc. The thermal efficiency of the device with a concentration of 0.04 to 0.02 nano-particles is estimated to be about 80% (Quezada-Garcia et al., 2019; Thappa et al., 2020).

Table 1 Model classifications

S.N.	*Models*	*Purpose*
1	Optical	Optical analysis
2	Thermal	Thermal analysis
3	Dynamic	Transient behaviour of receiver and overall dynamic analysis

The selection of modelling techniques depends on the criticality of the process and desired level of accuracy. When it is required to evaluate thermal performance quickly with reasonable accuracy, energy balance models are used. However, CFD models provide insight into heat and fluid phenomenon but involve the use of complex tools and higher computational cost (Amine et al., 2019). In this work, energy balance model has been used for quick assessment of thermal performance of line focus collectors. This developed model may be very useful for simple operations like water heating. The purpose of the work is to assess the thermal performance of line focus solar collectors for water heating using the thermal modelling. Results from the theoretical model are validated with data gathered from an experimental plant.

2 Thermal modelling

The thermal modelling describes the phenomenon of heat transfer from the heat flux received by the absorber to the working fluid. The thermal model of the solar collector is totally based on the idea of energy conservation. This model was created to calculate thermal characteristics such as collector outlet temperature; heat absorbed by water, heat losses to the environment, and power absorbed by water at different flow rates. A mathematical model is developed that takes into account all of the parameters that influence the thermal behaviour of water flowing through the receiver. This mathematical model is simulated using MATLAB programming. Figure 2 depicts a flowchart that describes the process for evaluating thermal parameters. Table 2 displays the model's input and output parameters.

The performance of a solar collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain and various losses. Thermal losses can be associated with heat transfer from liquid to the surrounding. Conduction, convection, and radiation are the three mechanisms of heat transfer that occur when heat travels from a liquid to its surroundings. Heat transmission occurs by convection from the liquid to the inner surface of the tube, conduction from the inner surface of the tube to the outside surface of the tube, and convection and radiation from the outer surface of the tube to the surrounding environment. Thermo-physical properties such as Nusselt number, Prandtl number, Reynolds number are suitably incorporated into the model.

$$\frac{1}{U_o} = \frac{1}{U_i} + \frac{D_o}{h_i D_i} + \frac{D_o \ln \frac{D_o}{D_i}}{2K} \tag{1}$$

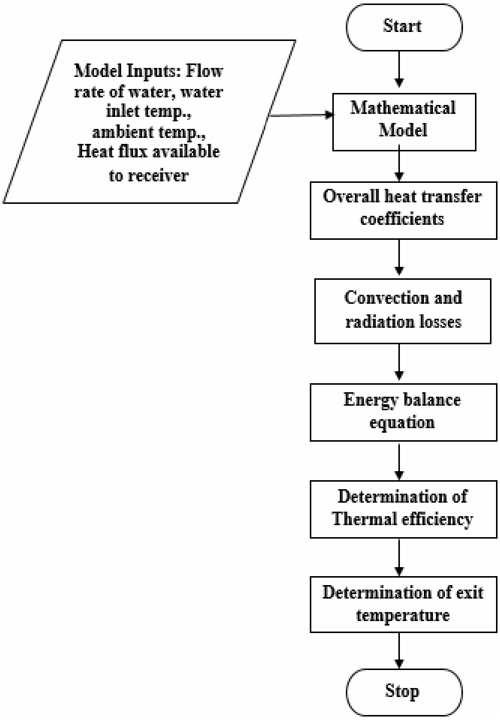
$$\frac{1}{U_i} = \frac{1}{h_w} + \frac{1}{h_r} \tag{2}$$

$$q_u = (FR) A_a \left[I_b - \left(\frac{A_p}{A_a} \right) U_i \left(T_p - T_a \right) \right] \tag{3}$$

$$\eta_{th} = \frac{q_u}{I_b A_a} \tag{4}$$

$$T_o = \frac{q_u}{m_f C_p} + T_p \tag{5}$$

Figure 2 Flowchart for the process of determining the thermal parameters



Equation (1) describes the overall heat transfer coefficients from liquid to surrounding in association with conduction, convection and radiation.

U_o and U_i stand for overall heat transfer and inside heat transfer coefficients, respectively. The outside and inside diameters of the receiver are designated as D_o and D_i, respectively. K and h_i, respectively, stand for thermal conductivity and convective heat transfer coefficient. Effects of convection and radiation are considered in equation (2). The coefficients of wind heat transfer and surface heat transfer are h_w and h_r, respectively. Energy balance equation across absorber pipe considering all kinds of losses and governing parameters is shown in equation (3). FR stands for heat removal factor, whereas A_p and A_a represent receiver and effective reflector area, respectively. I_b stands for beam radiation, while q_u stands for useful heat gain. T_p and T_a denote the inlet water and ambient temperature, respectively. Thermal efficiency and exit fluid temperature can be obtained by equations (4)–(5) (Incropera and DeWitt, 1999).

Table 2 Thermal model parameters

Model input parameters	*Model output parameters*
Flow rate of water (kg/sec)	Outlet temperature of water (°C)
Water inlet temperature (°C)	Useful heat gain by water (kW/m^2)
Ambient temperature (°C)	Heat loss (kW)
Heat available to the receiver (kW/m^2)	Thermal efficiency

3 Results and discussion

The developed thermal model is tested for exit temperature of water, heat flux available at the receiver, heat loss and thermal efficiency at different mass flow rates. Variations of intensity of radiation are also taken into account and the effect of the same on other parameters is also noticed. The model is simulated based on unit area of aperture irrespective of collector size. Table 3 shows the input parameters which are taken from a cooling plant located in the School of Engineering University of Seville, Spain (Pino et al., 2013). Thermal performance of the model is predicated for Ankleshwar, Gujarat, India by using the same input parameters except for climatic conditions of the location. In Table 4, the simulated findings of the model for thermal performance are summarised and compared to the experimental results.

Table 3 Input parameters of thermal model

Local time (Hrs.)	*Flow rate (kg/sec)*	*Ambient temp. (°C)*	*Radiation available to receiver (kW/m^2)*	*Inlet temp. (°C)*
13:00	2.80	27.5	0.426	137.2
13:30	2.92	28.8	0.433	142.3
14:00	3.39	29.0	0.423	158.5
14:30	3.39	29.5	0.363	158.9
15:00	3.55	30.1	0.251	169.4

3.1 Model validation

All simulated results obtained through this model are validated with experimental data taken from a cooling plant (Pino et al., 2013). It has been noticed that results are well-matched with each other. Performance parameters of the model are shown through the several plots. All plots comprise three curves; the closed curves are drawn for similar climatic conditions whereas the farthest one is the result for the climatic condition of Ankleshwar, Gujarat, India.

Table 4 Results of thermal model and its comparison with experimental results

Local time (Hrs.)	*Useful heat gain (kW/m²)*		*Heat loss (kW/m²)*		*Outlet temp. (°C)*	
	Simulated	*Experimental*	*Simulated*	*Experimental*	*Simulated*	*Experimental*
13:00	0.294	0.289	0.132	0.137	147.1	145.9
13:30	0.297	0.309	0.136	0.124	149.2	151.2
14:00	0.274	0.273	0.149	0.150	164.3	165.2
14:30	0.222	0.284	0.141	0.078	164.0	166.0
15:00	0.178	0.184	0.073	0.067	171.0	173.8

Figure 3 illustrates a plot of available heat flux versus local time. Heat gain by water has decreased as the intensity of radiation lowers in the afternoon. Other parameters, such as mass flow rate, ambient temperature, and water inlet temperature, have small effects that are not reflected.

Figure 3 Variation of heat flux with time (see online version for colours)

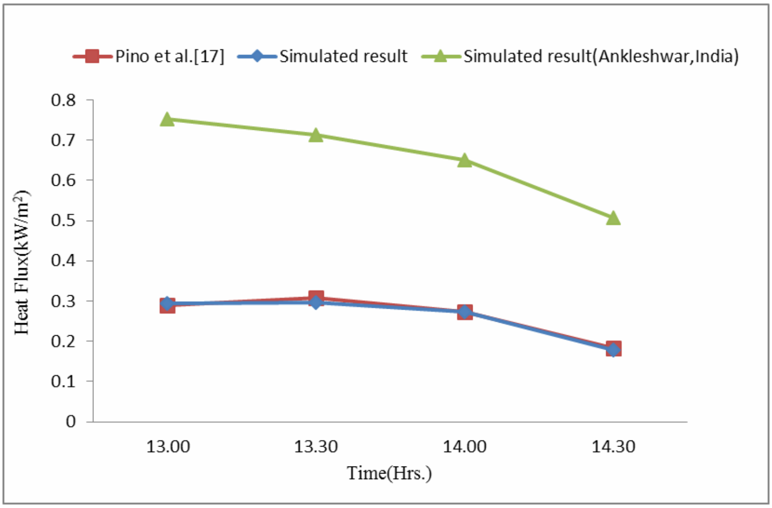


Figure 4 depicts a plot of heat loss fluctuations with respect to time. It can be seen that heat loss is greater at higher levels of radiation intensity. The receiver attends to more heat flux at higher intensities of radiation, resulting in a comparatively greater amount of heat loss to the surroundings. In Figure 5, a very important parameter, i.e., collector outlet temperature variations with local time is shown. The outlet temperature has been increasing with time. Besides intensity of the radiation, exit temperature also depends substantially on factors like mass flow rate and inlet temperature of the water.

Figure 4 Variation of heat loss per unit area with time (see online version for colours)

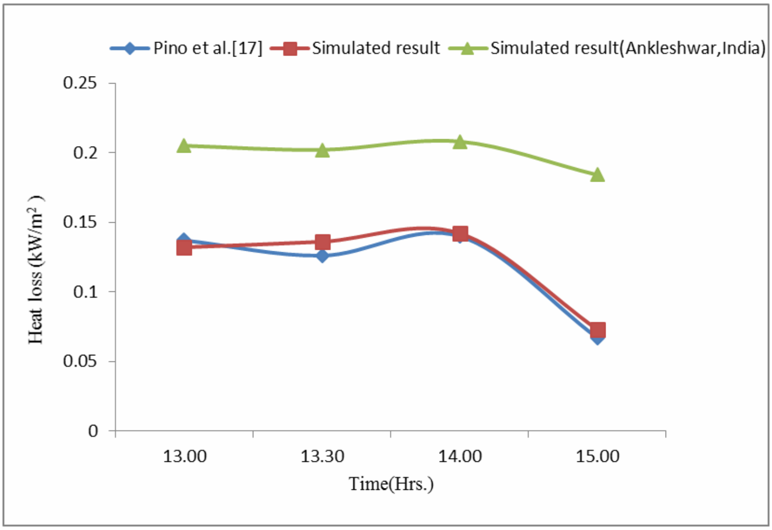
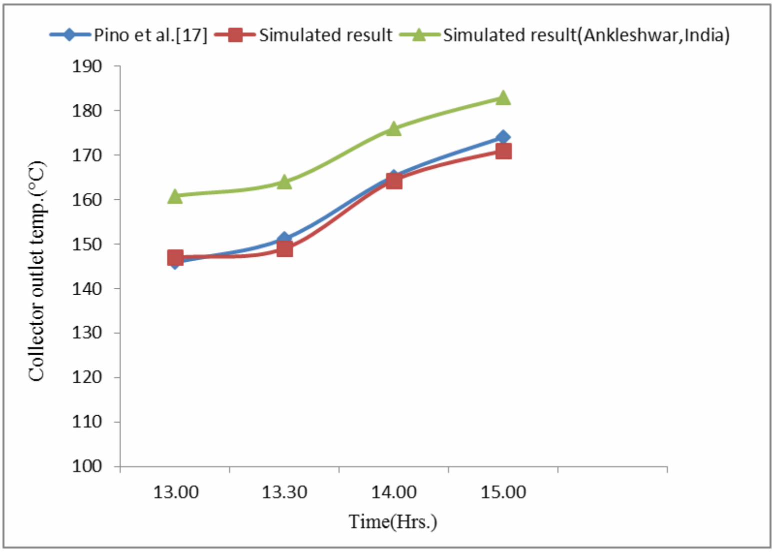
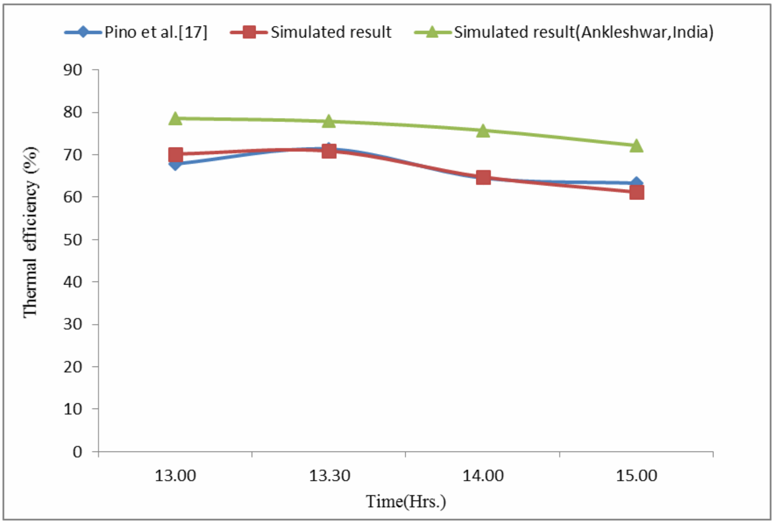


Figure 5 Variation of collector outlet temperature with time (see online version for colours)



A graph is drawn between thermal efficiency and local time as shown in Figure 6. It is observed that, thermal efficiency has been relatively reduced with time. Water has more time to remain in contact with the receiver pipe at lesser mass flow rates. This condition leads to more heat gain by water and hence results in high thermal efficiency.

Figure 6 Variation of thermal efficiency with time (see online version for colours)



4 Conclusions

Various kinds of solar collectors are commercially available which can meet the requirements of household or industrial application. Among them, line focus solar collectors are relatively cheaper than efficient point focus collectors due to their geometry and single axis tracking mechanism.

This paper encourages the adaption of line focus solar collectors mainly in the application of low heat requirements. In solar thermal technology, it is vital to develop a mathematical model for predicting the performance of solar collectors before the experimentation starts.

In this work, a thermal model is developed using an energy balance model for quick evaluation of thermal parameters. The results of the model have been compared and validated with the experimental results. The validated model has been used for water heating at the climatic conditions of Ankleshwar, Gujarat, India. As a part of thermal analysis, several important parameters are plotted with time for different mass flow rates and the intensity of radiation.

5 Expected outcomes

The developed thermal model can be used in water heating applications under any climatic condition.

On the basis of this model, a thermal design for line focus solar collectors can be done.

This model will help researchers validate the experimental investigation for such applications.

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Nomenclature

Symbols			
A_a	Effective reflector area (m^2)	K	Thermal conductivity (W/mK)
A_p	Absorber surface area (m^2)	m_f	Mass flow rate (kg/sec)
D_i	Inside diameter of receiver (m)	q_u	Useful heat gain (W)
D_o	Outside diameter of receiver (m)	T_a	Ambient temp. (°C)
FR	Heat removal factor	T_o	Exit water temp. (°C)
h_i	Inside heat transfer coefficient (W/m^{2}K)	T_p	Inlet water temperature (°C)
h_r	Surface heat transfer coefficient (W/m^{2}K)	U_i	Inside heat transfer coefficient (W/m^{2}K)
h_w	Wind heat transfer coefficient (W/m^{2}K)	U_o	Overall heat transfer coefficient (W/m^{2}K)
I_b	Direct radiation (W/m^2)	η_{th}	Thermal efficiency