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Design Support System for Parabolic Trough Solar Collector

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Abstract: Parabolic Trough Collector (PTC) is special kind of heat exchanger that is able to transfer solar radiation energy to fluid medium that flow through it. Designing a PTC for a specific working condition requires determination of several parameters and referring to a number of design standards and handbooks. Hence, a design support system is required to determine the necessary parameters and simulate different working conditions. Although, a number of design support systems for solar collectors are available in the market, they are either expensive or limited to certain types of solar collectors. This study presents an in-house design simulation software for parabolic trough collector. The simulation software was coded in Microsoft Visual Studio.Net 2010. Through its Graphical User Interface (GUI), the software allows the user to give input parameters, explore built in standards and review outputs. The output parameters include geometric design parameters, heat losses coefficient and efficiencies. The output parameters are important in the initial stage of designing parabolic trough collectors to reduce design time and effort. The results of the simulation software are validated with published experimental and analytical results.

Key words: Parabolic trough collector, design support system, solar thermal collector

INTRODUCTION

Solar thermal collectors are special kind of heat exchangers that are able to transform solar radiation energy to internal energy of the transport medium such as air, water, oil, etc. (Kalogirou, 2004). Solar thermal collector can be categorised as concentrating (sun tracking) and non-concentrating (stationary). Non-concentrating collectors usually have the same area for intercepting and absorbing solar radiation while concentrating collectors usually have a concave reflecting area to increase the radiation flux. Parabolic trough collectors are concentrating type of solar thermal collector whose working temperature can reach up to 400°C. The main components of parabolic trough collector are parabolic shaped reflector, receiver, support structures, sun tracking mechanism and transport mechanism for the heat transfer fluid.

Designing a parabolic trough collector involve large number of calculations to determine design parameters and requires referring to several handbooks and database specially for new designers. On the other hand, the use of design support systems (simulation software) can reduce the design time and effort. Furthermore, simulation software can be used to predict the performance and optimize the design parameters without incurring cost of prototype testing. Thus, simulation software is required to act as design support system in order to reduce cost and time.

There are a number of design support systems for solar thermal collectors. One example of in house simulation software was KOLEKTOR 2.2 which was developed by Matuska *et al*. (2008) at Czech Technical University. KOLEKTOR 2.2 is user-friendly simulation software used for detailed modelling of solar thermal flat-plate collectors. The software was developed using Microsoft Visual Basic .NET framework. Their mathematical model is based on internal and external energy balance of the absorber solved in iteration loops to determine the temperature distribution and heat transfer coefficient in main parts of solar collector. KOLEKTOR 2.2 was developed with the intention to overcome some of the limitations in the features of CoDePro program and TRNSYS Type 103, which do not allow energy performance modelling of advanced solar collectors. However, these simulation design support tools are limited to flat plate collectors. In this study, an in house design support system specifically developed for parabolic trough collectors is presented. This study is intended to present the features and capabilities of the design support system.

PTC together with sun tracking mechanism (Khatib *et al*., 2009) can be considered as environment friendly alternative energy source (Manikandan *et al*., 2012).

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MATHEMATICAL MODELING

The design parameters are determined from geometric relations for parabolic reflector, circular receiver and the sun incident angle as follows (Duffie and Beckman, 2006; Kalogirou, 2009).

Concentration ratio, is the ratio of the area of aperture to area of receiver given by:

$$\text{Concentration Ratio, CR} = \frac{A_a}{A_r} \tag{1}$$

Rim angle is given as:

$$\phi_r = \sin^{-1}\left(\frac{W_a}{2r_r}\right) \tag{2}$$

For any point of the parabolic reflector the local mirror radius is.

Aperture Width:

$$r = \frac{2f}{1+\cos\phi_r} \tag{3}$$

$$W_a = 4f\tan\frac{\phi_r}{2} \tag{4}$$

From the aperture width, aperture area can be calculated by:

$$A_a = W_a \text{ X } L \tag{5}$$

Focal length:

$$f = \frac{W_a}{4\tan\left(\frac{\phi_r}{2}\right)} \tag{6}$$

The vertical height of the parabola is given by:

$$h_p = \frac{W_a^2}{16f} \tag{7}$$

Arc Length of parabolic Curve (Curve length of parabolic surface):

$$S = \frac{H_p}{2}\left\{\sec\left(\frac{\phi_r}{2}\right)\tan\left(\frac{\phi_r}{2}\right) + \ln\left[\sec\left(\frac{\phi_r}{2}\right) + \tan\left(\frac{\phi_r}{2}\right)\right]\right\} \tag{8}$$

where, H_p is the latus rectum of the parabola is equal to aperture width, W_a if rim angle $\phi_r = 90°$.

Thus, surface area of the concentrator is given as:

$$A_s = S \text{ x } L \tag{9}$$

The diameter for cylindrical receiver would be given by:

$$D_o = 2r_r \sin\theta_m \tag{10}$$

Optical efficiency, η_o is defined as the ratio of the energy absorbed by the receiver to the energy incident on the concentrator's aperture which given as:

$$\eta_o = \rho_m \tau\alpha\gamma\left(\left(1 - A_f \tan\theta\right)\cos\theta\right) \tag{11}$$

Geometric factor, A_f is the ration of the shaded area to the aperture area:

$$A_f = \frac{A_l}{A_a} \tag{12}$$

where, shaded area, A_l is:

$$A_l = \frac{2}{3}W_a h_p + fW_a\left(1 + \frac{W_a^2}{48f^2}\right) \tag{13}$$

Heat loss coefficient, U_L, based on the receiver area A_r, is given by:

$$U_L = \left[\frac{A_r}{\left(h_w + h_{r,c-a}\right)A_g} + \frac{1}{h_{r,r-c}}\right]^{-1} \tag{14}$$

The linearized radiation loss coefficient from cover to ambient, $h_{r,\ c\text{-}\alpha}$ is given as:

$$h_{r,c-a} = \varepsilon_g \sigma\left(T_g + T_a\right)\left(T_g^2 + T_a^2\right) \tag{15}$$

While the linearized radiation coefficient from receiver to cover, $h_{r,\ r\text{-}c}$ is given as:

$$h_{r,r-c} = \frac{\sigma\left(T_r^2 + T_c^2\right)\left(T_r + T_c\right)}{\frac{1}{\varepsilon_r} + \frac{A_r}{A_c}\left(\frac{1}{\varepsilon_c} - 1\right)} \tag{16}$$

Wind loss coefficient, h_w for PTC is given as:

$$h_w = h_{c,c-a}\frac{(Nu)k}{D_g} \tag{17}$$

where, the boundary condition is given as:

$$0.1 < Re < 1000, \quad Nu = 0.4 + 0.54(Re)^{0.52} \tag{18}$$

$$1000 < Re < 50,000, \quad Nu = 0.3(Re)^{0.6} \tag{19}$$

Overall heat loss coefficient based on receiver tube outside diameter is given as:

$$U_o = \left[\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \frac{D_o \ln\left(D_o / D_i \right)}{2k} \right]^{-1} \tag{20}$$

where h_{fi}, is convective heat transfer inside receiver tube:

$$h_{fi} = \frac{(Nu)k}{D_i} \tag{21}$$

where for Re>2300:

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4} \tag{22}$$

For laminar flow Re<2300:

$$Nu = 4.364$$

Heat Removal Factor is the ratio of the heat actually delivered to that delivered if the collector plate were at uniform temperature equal to that of the entering fluid:

$$F_R = \frac{mC_p}{A_r U_L} \left(1 - \exp\left[-\frac{U_L F' A_r}{mC_p} \right] \right) \tag{23}$$

where, F' is the collector efficiency factor given as:

$$F' = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \left(\frac{D_o}{2k} + \ln \frac{D_o}{D_i} \right)} = \frac{U_O}{U_L} \tag{24}$$

Thus, useful energy delivered by collector is given as:

$$q_c = F_R \left[\eta_o I_c A_a - U_L (T_r - T_a) A_r \right] \tag{25}$$

And Instantaneous efficiency is:

$$\eta_c = F_R \left[\eta_o - U_L \frac{(T_r - T_a)}{I_c C} \right] \tag{26}$$

The above Eq. 1-26 will be used to determine different parameters in the parabolic trough collector design support system.

DESIGN SUPPORT SYSTEM

The Mathematical model has been transformed into a design support system (simulation software). In addition to the mathematical model design charts, material properties and standards from handbooks have been included in the database.

The design support system is a computer program developed by using Microsoft Visual Studio.Net 2010 programming language which is open source software. The program has a user friendly graphical user interface where the user can give inputs and compute results with push buttons and menus. An installable version of the software can be installed on computers which do not require the source code and the programming environment to use. When the program is started an initial window with three tabs will be displayed. The initial tab is for geometric design as show in Fig. 1. The geometric design tab is used to determine design parameters for the collector, receiver and glass cover. The schematic diagram with calculated values will be obtained as an output as shown in Fig. 2.

The next tab is functional analysis where the varies loss coefficients can be determined based on the input parameters such as material properties, heat transfer fluid properties and operating environment (temperature and wind). The screenshot of functional analysis tab is shown in Fig. 3.

Performance analysis tab is used to simulate the performance as shown in Fig. 4. Optical and instantaneous efficiencies are calculated in this window.

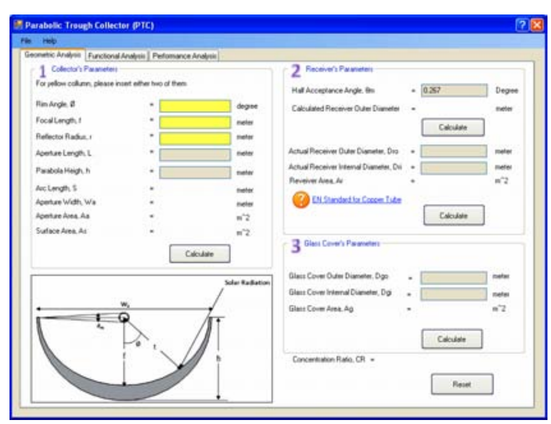

Fig. 1: Screenshot of geometric design tab

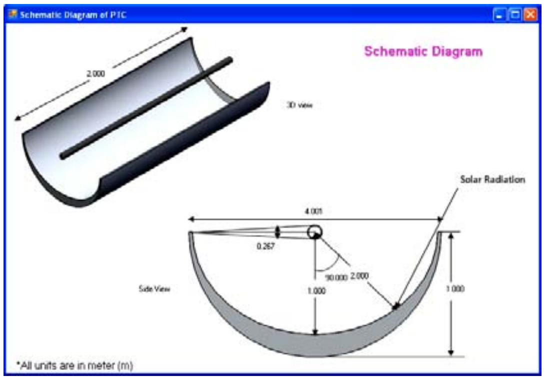

Fig. 2: Schematic diagram of design parameters

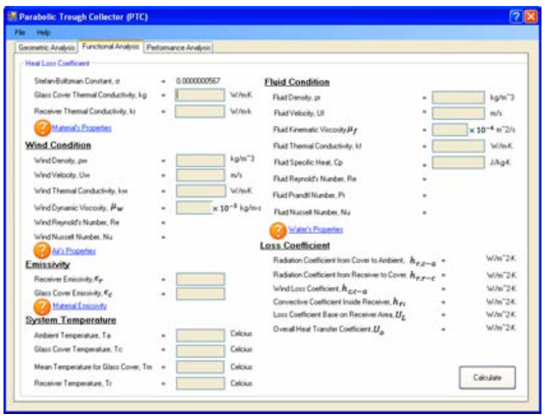

Fig. 3: Screenshot of functional analysis tab

Fig. 4: Performance Analysis tab

Finally, a design summary will be displayed both textually and schematically.

The developed design support system can be used to simulate different working conditions and come up with the best design option.

VALIDATION OF THE RESULT

The output result from the design support system has been verified with previously published results and is in good agreement. The geometric analysis outputs were validated with data Garcia-Valladares and Velazquez (2009) have used to validate their model and the percentage error is within 5%. Similarly, the functional and performance analysis results from the parabolic trough simulation software were compared with the data from (Kalogirou, 2009) and the percentage error is within 5%. The possible sources of error for a variation in the result are round off errors, differences in modelling and insufficient data to simulate exactly the same situation.

CONCLUSION

A design support system for parabolic trough collector design is presented in this study. The results of the software were validated with published works. With respect to the user friendliness of the developed software, evaluation tests were performed with selected final year mechanical engineering students. The feedback from the students was incorporated in the final version of the software. The current version of the design support system is limited to parabolic trough thermal collectors. Future work should address adding more modules to design other types of solar collectors.

Such design support systems can be used to reduce the design time by simulating different working conditions easily. The design standards and database included in the software reduce the time to search for information. Furthermore, the developed design support system can be used by novice designers and as a teaching aid in academia.

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NOMENCLATURE

A_a = Aperture Area (m^2)
A_c = Glass Cover Area (m^2)
A_f = Geometric Factor
A_r = Receiver Area (m^2)
A_s = Surface area of collector (m^2)
A_l = Aperture area loss (m^2)

C_p = Specific heat at constant pressure (J kg K^{-1})
CR = Concentration Ratio
D_i = Tube inside diameter (m)
D_o = Tube outside diameter (m)
F' = Collector efficiency factor
f = Focal distance (m)
F_{as} = Shape factors
F_R = Heat removal factor
h_{fi} = Convective heat transfer coefficient inside receiver (W $m^2 K^{-1}$)
H_p = Latus rectum of the parabola (m)
h_p = Height of the parabola (m)
I_r = Solar flux (W m^{-2})
I_a = Aperture flux (W m^{-2})
K_f = Fluid thermal conductivity (W $m^2 K^{-1}$)
K_g = Glass cover thermal conductivity (W $m^2 K^{-1}$)
K_r = Receiver tube thermal conductivity (W $m^2 K^{-1}$)
K_w = Wind thermal conductivity (W $m^2 K^{-1}$)
L = collector length (m)
m = Mass flow rate (kg sec^{-1})
η_c = Instantaneous Efficiency
η_o = Optical efficiency
Nu = Nusselt number
Pr = Prandtl number
q_L = Heat loss (W)
η_u = Useful energy delivered by the collector (W)
Re = Reynold's Number
R_k = Composite thermal resistance (K W^{-1})
r_r = Receiver radius (m)
S = Arc length of Parabolic Curve (m)
T_a = Ambient Temperature (°C)
T_c = Collector/Aperture Temperature (°C)
T_g = Glass cover temperature (°C)
T_r = Receiver Temperature (°C)
U_L = Solar collector heat transfer loss coefficient (W m^2 °C^{-1})
U_o = Overall heat transfer coefficient
W_a = Collector aperture (m)
θ_m = Half acceptance angle (degrees)
ϕ_r = Collector rim angle (degrees)
ρ = Density kg m^{-2}
ρ_m = Reflectance of the mirror
τ = Transmittance of the glass cover
α = Absorptance of the receiver
γ = Intercept factor
θ = Angle of incidence (degrees)
ε_g = Emissivity of glass covers
ε_r = Emissivity of receiver
σ = Stefan-Boltzman constant [= 5.67×10^{-8}] (W $m^2 K^{-4}$)

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