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Full Length Article

A new non-iterative friction factor correlation for heat transfer fluids in absorber tube of parabolic trough collector

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ABSTRACT

In this study, friction factors of heat transfer fluids (HTFs) that flow through the absorber tube in parabolic trough collector (PTC) are compared with using correlations. Syltherm 800 and Therminol VP-1 HTFs are considered for this study. Also, turbulent flow and rough pipe are considered for evaluation of the correlations of friction factor. The aim of this study is to compare a new non-iterative friction factor model, which is established for this study, with several alternative models against the Colebrook equation for friction factor and its effects on the relative error of pressure drop, Nusselt number estimated from the Gnielinski equation and heat transfer coefficient. All correlations are evaluated according to having mean absolute relative error (MARE) and root mean square error (RMSE). It is obtained that Reynolds number of Therminol VP-1 and Syltherm 800 are ranged from 1.1×10^4 to 2.97×10^6 and from 3.8×10^3 to 1.33×10^6, respectively. And, it is observed that friction factor of Syltherm 800 is higher than Therminol VP-1 at the same fluid temperatures. The results show that the new model established for this study is the closest correlation to the results of the Colebrook equation with having the lowest value of MARE and RMSE. MARE values of the new model is ranged in 0.01–0.02% for both Therminol VP-1 and Syltherm 800, and RMSE values of the new model are obtained as 3.78×10^{-6} and 5.57×10^{-6} for Therminol VP-1 and Syltherm 800, respectively.

1. Introduction

A high performance solar collector is required to deliver high temperature with good efficiency. Because of light structures and low-cost technology has made solar thermal collectors to produce temperatures up to 400 °C. One of these systems is parabolic trough collectors (PTC) can effectively produce temperatures between 50 and 400 °C [1].

PTC are made of reflective surface that is typically covered selective coating, concentrates solar radiation on the absorber tube which is at the focus of the reflector a long line. The basic principle of PTC is to increase the temperature of fluid which passes through absorber tube by concentrating solar radiation on the absorber tube. The absorber of PTC is usually tubular, enclosed in a glass tube to reduce convective losses [2].

Performing analyses of PTC have been important subject for the researchers. There are some studies about experimental investigation of thermal performance of PTC [3–5]. Additionally, many of published studies of PTC are concerned with the LUZ trough collector used in the Solar Thermal Electric Generation Systems (SEGS) plant at Kramer Junction, in southern California [6–12]. Sandia National Laboratories performed test on a typical solar PTC with non-evacuated and evacuated tubular receivers to determine the thermal loss and collector efficiency of the LS2 SEGS2 and a computer model was developed to compare model predictions with experimental data [13].

In literature, there are many studies about numerically investigation of behaviour of heat transfer fluids in absorber tube of PTC [7–15]. And, one of the most important phenomena in mathematical modeling of heat transfer fluids is friction factor. The friction factor is used both in calculation of pressure drop and heat transfer of fluids [16].

Friction factor have been investigated by some researchers, recently. Kiijärvi [17] compared friction factors that are correlated with three different equations to the Colebrook equation. Results show that both the Swamee-Jain and Haaland equation can be used instead of the Colebrook equation for both smooth and rough pipe in the range of Reynolds number from 2300 to 10^5 and ε/D from 0 to 0.00025. Fang et al. [18] compared correlations of single-phase friction factor of flow for both smooth and rough pipes. New correlations of the single-phase friction factor for turbulent pipe flow were developed in the range of Reynolds number from 3000 to

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Nomenclature

D	Inner diameter of pipe [m]	Cp	Specific heat capacity [J/(kg.°C)]
ε	Roughness of pipe [m]	ΔP	Pressure drop per metre [Pa/m]
$\dot{V}$	Volumetric flow rate [gpm]	RE	Relative error
ρ	Density of fluid [kg/m^3]	$MARE$	Mean absolute relative error
v	Velocity of fluid [m/s]	N	Total data points
f	Friction factor	i	Integer starting from 1 to N
$\dot{m}$	Mass flow rate (kg/s)	y	Determined value
Re	Reynolds number	$RMSE$	Root mean square error
μ	Dynamic viscosity [Pa.s]		
Nu	Nusselt number	*Subscripts*	
k	Thermal conductivity [W/(m.°C)]	pre	Predicted
h	Heat transfer coefficient [W/(m^2.°C)]	st	Standard
Pr	Prandtl number		

10^8 and ε/D from 0 to 0.05. Fang et al. [19] investigated pressure drop and friction factor correlations of supercritical flow. A new correlation for supercritical friction factor was proposed and it was found that this new correlation reduced the mean absolute relative error (MARE) by more than 10% compared with the best existing model. Huang et al. [20] investigated a three dimensional numerical model of parabolic trough receivers with and without helical fins, protrusions and dimples. The simulation on the fully developed turbulent flow and heat transfer in the inner tube was done with using Therminol VP-1 at Reynolds number ranged from 1×10^4 to 2×10^4. It was obtained that the relative error of friction factor was less than 7.84% for smooth tube. Further, there are some studies about relationship between nanofluids and friction factors in a tube [21–22].

However, the Colebrook equation has become the acceptable standard for the calculation of friction factor in turbulent pipe flow,

Table 1
Specification of the experimental data for parabolic trough collector [9,13].

Inner diameter of absorber tube, D	0.066 m
Roughness of absorber tube, ε	0.0000015 m
Volumetric flow rate of HTF, $\dot{V}$	50 gpm

Table 2
Correlations (against to the Colebrook equation) of friction factor covering roughness for turbulent flow.

Rank	Model name	Correlations
1	Moody [26]	$f = 5.5x10^{-3}[1 + (2x10^4(\varepsilon/D) + 10^6/Re)^{1/3}]$
2	Eck [27]	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon/D}{3.71} + \frac{15}{Re}\right)$
3	Jain [28]	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon/D}{3.715} + \left(\frac{6.943}{Re}\right)^{0.9}\right)$
4	Swamee-Jain [29]	$f = 1.325\left[ln\left(\frac{\varepsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2}$
5	Churchill [30]	$f = 8\left[\left(\frac{8}{Re}\right)^{12} + \left(\left(2.457ln\left(\left(\frac{7}{Re}\right)^{0.9} + 0.27(\varepsilon/D)\right)^{-1}\right)^{16} + \left(\frac{37530}{Re}\right)^{16}\right)^{-1.5}\right]^{1/12}$
6	Chen [31]	$f = \left(-2log_{10}\left[\frac{\varepsilon/D}{3.7065} - \frac{5.0452}{Re}Log_{10}\left(\frac{(\varepsilon/D)^{1.1098}}{2.8257} + \frac{5.8506}{Re^{0.8981}}\right)\right]\right)^{-2}$
7	Round [32]	$f = [-1.8\log(0.135(\varepsilon/D) + 6.5/Re)]^{-2}$
8	Schorle et al. [33]	$\frac{1}{\sqrt{f}} = \left[-2\log_{10}\left(\frac{\varepsilon/D}{3.7} - \frac{5.02}{Re}\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{14.5}{Re}\right)\right)\right]$
9	Barr [34]	$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{5.158\log(Re/7)}{Re\left(1+\frac{Re^{0.52}}{29}\left(\frac{\varepsilon}{D}\right)^{0.7}\right)}\right)$
10	Zigrang and Sylvester [35]	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon/D}{3.7} - \frac{5.02B}{Re}\right), A = \log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{13}{Re}\right), B = \log_{10}\left(\frac{\varepsilon/D}{3.7} - \frac{5.02A}{Re}\right)$
11	Haaland [36]	$f = \left[-0.782ln\left(\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right)\right]^{-2}$
12	Manadilli [37]	$\frac{1}{\sqrt{f}} = \left[-2\log\left(\frac{\varepsilon/D}{3.7} + \frac{95}{Re^{0.983}} - \frac{96.82}{Re}\right)\right]$
13	Romeo et al. [38]	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon/D}{3.7065} - \frac{5.0272B}{Re}\right)A = \log_{10}\left[\left(\frac{\varepsilon/D}{7.7918}\right)^{0.9924} + \left(\frac{5.3326}{208.815+Re}\right)^{0.9345}\right], B = \log_{10}\left(\frac{\varepsilon/D}{3.827} - \frac{4.567A}{Re}\right)$
14	Sonnad and Goudar [39]	$\frac{1}{\sqrt{f}} = 0.8686\ln\left(\frac{0.4587Re}{(C-0.31)^{\frac{C}{C+1}}}\right), C = 0.124Re\frac{\varepsilon}{D} + \ln(0.4587Re)$
15	Avci and Karagoz [40]	$f = 6.4/\left[ln(Re) - \ln\left(1 + 0.01Re\frac{\varepsilon}{D}\left(1 + 10\sqrt{\varepsilon/D}\right)\right)\right]^{2.4}$
16	Papaevangelou [41]	$f = \frac{0.2479-0.0000947(7-\log(Re))^4}{\left(\log\left(\frac{\varepsilon/D}{3.615}+\frac{7.366}{Re^{0.9142}}\right)\right)^2}$
17	Fang et al. [18]	$f = 1.613\left[\ln\left(0.234(\varepsilon/D)^{1.1007} - \frac{60.525}{Re^{1.1105}} + \frac{56.291}{Re^{1.0712}}\right)\right]^{-2}$
18	Ghanbari et al. [42]	$f = \left[-1.52\log\left(\left(\frac{\varepsilon/D}{7.21}\right)^{1.042} + \left(\frac{2.731}{Re}\right)^{0.9152}\right)\right]^{-2.169}$
19	Offor and Alabi [43]	$f = \left[-2log_{10}\left(\frac{\varepsilon/D}{3.71} - \frac{1.975}{Re}ln\left(\left(\frac{\varepsilon/D}{3.93}\right)^{1.092} + \frac{7.627}{Re+395.9}\right)\right)\right]^{-2}$