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Similarity analysis of parabolic-trough solar collectors

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HIGHLIGHTS

- A new method of analyzing PTCs using similarity principle and dimensional analysis is proposed.
- The MCRT method is employed to calculate the solar-energy flux on the absorber tube.
- The numerical results are in good agreement with literature data for the scaled models.
- This study can help significantly lower the entrance threshold for performing experimental solar-thermal studies.

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ABSTRACT

A new method of analyzing the thermal performance of parabolic trough collectors (PTCs) for solar thermal applications is established using similarity principle and dimensional analysis, through which different types of PTCs can be studied via a single scaled physical model. Six dimensionless numbers for the PTC are drived and are used to build a scaled PTC model. A coupled approach combining Monte-Carlo ray-tracing method with finite-element is developed to analyze the performance of PTCs. Experimental data from the literature are employed to calibrate the numerical model. Compared with the results of four typical cases of non-scaled experimental data obtained from the literature, differences in average efficiencies of the scaled-down models are within 0.75%, thereby validating the scaled model and similarity method for analyzing PTCs with vastly different length scales. Effects of direct normal irradiance (DNI) and temperature difference between the receiver fluid and ambient air ΔT_{ab} on the efficiency of PTCs are further analyzed using the scaled model. The simulation results indicate that the collector efficiency increases with the augmentation of the DNI, whereas it decreases with the increase in ΔT_{ab}. The similarity analysis method provides a new perspective for solar-thermal research by demonstrating the possibility of performing experiments on PTC on a much-reduced length scales.

1. Introduction

Solar energy is a vast, sustainable, and clean source of energy. Mainstream solar technologies such as concentrated solar power (CSP) systems and photovoltaics have the potential to meet global energy demand with reduced (if not zero) greenhouse-gas emissions. In CSP systems, three types of solar collectors, including parabolic trough, tower, and dish, are widely used in concentrating sunlight [1–3]. Among such solar-thermal power generation technologies, the parabolic-trough-based CSP is by far the most mature and cost-effective one widely used in mid/low temperature solar-energy utilization with different kinds of working fluid [4,5].

In recent years, a significant amount of studies have been conducted on the analysis of PTCs both experimentally and numerically. Dudley et al. [6] tested the performance of SEGS LS-2 PTC by coating cermet and black chrome on the exterior of metal-absorber tube under the circumstances of vacuum or air in the annulus and bare tubes. Moreover, fitting equations for collector efficiency and thermal losses were developed based on experimental results, which were widely used as a prototype in many numerical studies. Liang et al. [7] summarized and compared different one-dimensional (1-D) mathematical models under various assumptions and conditions and established an accurate 1-D model that was sufficiently precise compared with the result of the three-dimensional (3-D) model in the literature [8]. Padilla et al. [9] also carried out a detailed 1-D thermal analysis of a PTCs, but considering the thermal interaction between adjacent surfaces to accurately evaluate radiation losses. They built a model capable

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Nomenclature

C_p	heat capacity (kJ kg^{-1} K^{-1})
D	diameter (m)
D_1	absorber outer diameter (m)
D_2	glass inner diameter(m)
D_3	absorber inner diameter(m)
F	focal length (m)
h	convection heat-transfer coefficient (W m^{-2} K^{-1})
l	axial length of receiver (m)
l_0	multiple of scale down
Nu	Nusselt number
Pr	Prandtl number
$\dot{q}$	concentrated heat flux (kW m^{-2})
Q_m	mean volumetric flow rate (L min^{-1})
Re	Reynolds number
T	temperature (K)
T_1	temperature of outer surface of absorber (K)
T_2	temperature of glass envelope (K)
T_3	temperature of inner surface of absorber (K)
T_4	temperature of HTF (K)
T_{in}	temperature of fluid flowing into the tube (K)
T_{out}	temperature of fluid flowing out of the tube (K)
u	velocity of working fluid (m s^{-1})
W	aperture width (m)
ΔT	temperature difference of fluid between the entry and exit of the tube (K)
ΔT_{ab}	receiver-fluid temperature above ambient air temperature (K)

Greek symbols

α	absorptance of glass envelope
ε	turbulence dissipation rate or emissivity
ε_1	emissivity of selective coating
ε_2	emissivity of glass envelope
η	efficiency of test data
η'	calculated efficiency
κ	turbulent kinetic energy
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
σ	Stefan Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
σ_T	turbulent Prandtl number
σ_k	turbulent Prandtl numbers for diffusion of κ
σ_ε	turbulent Prandtl numbers for diffusion of ε
φ_{rim}	rim angle

Subscripts and superscripts

s	scaled model
p	prototype
d	dimensionless
n	normal direction

of accurately calculating heat losses and collector efficiency under different operating conditions. Huang et al. [10] proposed a two-dimensional (2-D) thermal model to calculate heat losses quickly and accurately considering the radiation losses from the side plate of a stainless steel and direct transmission of long-wave radiation by the glass envelope. However, in the 1-D and 2-D models, solar flux and flow were assumed uniform, making it virtually impossible to investigate the realistically significant influence of non-uniformity in temperature distribution of the heat transfer fluid (HTF) in the circumferential direction on the performance of PTCs. Therefore, 3-D numerical models are often necessary [1]. Wang et al. [11] investigated thermal performances of a PTC system considering non-uniform flux distribution in the circumferential direction of an inner metal-absorber tube and analyzed circumferential temperature difference of the absorber tube for various fluid-inlet temperatures, velocity, and solar radiation. A similar method was used to investigate the thermal performances of a PTC using molten salt as the HTF [12]. Ravi et al. [13] proposed a porous disc line receiver for a PTC, which helped to improve heat-transfer characteristics of the receiver owing to an increase in the heat-transfer area, thermal conductivity, and turbulence. However, a trade-off had to be made with the resulting pressure drop increases. He et al. [8] and Wu et al. [14] both established a coupled method by combining the Monte Carlo ray tracing (MCRT) method and the finite-volume method to simulate the photo thermal and heat-transfer processes occurring in a PTC using a 3-D model. Non-uniform heat-flux distribution on the surface of the inner tube was calculated using the MCRT method taking into account finite size of the sun, which acts as one of the boundary conditions in the modeling process. The results were in good agreement with the experimental data.

In some engineering fields, similarity principle and dimensional analysis serve as important theoretical basis for porotype analyses since scaled models allows for time and cost savings. A scaled model is considered to have similarity with those of real applications only if the two share a similarity in geometric, kinematic, and dynamic properties. The principle of the dimensional analysis is that certain physical laws do not depend on basic units of measurement [15]. Zou et al. [16] developed a small-scaled PTC to heat water in cold areas. The thermal efficiencies reached approximately 67%, which was better than that obtained from conventional flat-plate solar collectors. Hence, different types of PTCs can be studied and their characteristics can be analyzed via a single physical model by employing dimensional analysis.

Additionally, to better understand the velocity and heat-flux distribution characteristics, several experimental and simulative studies on PTCs have been conducted [17–20]. However, in most of the parametric and/or mechanistic experimental studies, only one or two segments of heat collecting elements (HCEs) were employed, and the corresponding numerical studies usually adopted the same layout, which were shorter than those observed in commercial applications. Because the temperature of HTF increases gradually, and because the characteristics of PTCs largely depend on temperature, using one or two segments of HCEs in the simulation or experiment is insufficient for studying the performance of PTCs. However, conducting studies at full scale is usually prohibitive experimentally and 3-D numerically.

In this study, a new method of analyzing PTC systems is developed using similarity principle and dimensional analysis. First, six dimensionless numbers for PTCs are obtained using dimensional analysis. Second, a 3-D numerical model is calibrated based on the experimental data published by Sandia National Laboratories [6] using finite element method (FEM). Third, based on similarity principle and dimensional analysis, scaled models of PTCs are developed. Simulated thermal efficiency and temperature are compared with those of experimental data. Ultimately, reduced-scaled models are used to investigate thermal performances of PTCs under particular conditions. The results are compared with the fitting equation obtained from Sandia National Laboratories [6].

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