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Optimizing the design of receiver in parabolic trough by using genetic algorithm

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ABSTRACT

Solar energy is critical for the power needs. The pipe design of parabolic trough in solar energy application systems is critical in the collection of solar energy. Pipes with micro-grooves etched in the inner wall have been widely utilized not only as cooling systems but also as absorber receivers in parabolic troughs for solar thermal absorbers because microgrooves improve heat transfer between the inside and outside walls of the pipe. Liquid is automatically pumped vertically along the microgrooves on the inner pipe wall by capillary force, thus resulting in increased surface heat exchange. This study aims to determine the optimum design for parabolic troughs in solar energy application systems. In line with this, a capillary-driven two-phase flow model was constructed to investigate the liquid behavior in grooved pipes and to maximize heat transfer in the pipes. Specifically, this study examined the influence of different microgrooves, fluids, temperatures, radii, and widths of grooves to analyze the maximum liquid front position in the inner wall pipe and to optimize the pipe design via genetic algorithm. Results show that the proposed genetic algorithm can solve more accurately the heat exchange problem and provide an optimal solution which has larger wetting front compared with previous research.

1. Introduction

Solar thermal power plants use high-temperature steam to generate electricity. Solar thermal power plants and conventional power plants differ basically because the latter utilizes gas, coal, or oil, whereas the former relies on the sun as its main source of energy to drive its turbines. Parabolic mirrors are placed in long rows in solar thermal power plants to concentrate solar irradiation up to 80 times on the absorber tube, increasing the temperature of the transfer fluid to around 400 °C. This structure is described as parabolic trough. Parabolic trough power plants are appropriate for industrial scale applications with electrical power ranging from 50 to 200 MW. Parabolic trough power plants can replace conventional power plants without replacing their network structure. Constructing hybrid power plants is possible because solar fields can feed heat energy into conventional steam turbines. For instance, parabolic trough power plants can be combined easily with clean natural-gas-fired integrated-cycle power plants. Retrofitting existing conventional steam power plants with parabolic trough solar field as an extra steam generator will further improve the energy efficiency of the power plant. Among all solar technologies, the parabolic trough has the least material requirement.

Many studies have focused on parabolic troughs because of their potential for cost reduction. For example, several studies have examined reflectors [1–5] and some attempts have been made on absorber receivers [6–9]. However, limited studies have investigated the microgrooves of absorber receivers. Pipes with microgrooves should be applied in the absorber receivers of parabolic trough and cooling systems because microgrooves can improve heat transfer by enhancing convective boiling and capillary flow. Many studies have focused on capillary systems. For instance, Marche [10] studied the capillary effects of a 2D viscous shallow water model [10], and Yoon and Semenov [11] investigated the capillary cavity flow in a circular cylinder. In another study, Vanaparthy and Meiburg [12] analyzed the miscible displacements in capillary tubes through variable density and viscosity. However, limited studies have focused on integrating the capillary system into the absorber receiver of a parabolic trough, a device that could enhance heat exchange in solar energy power plants. Peterson [13] initiated the study of micro-grooved heat exchanger. However, Peterson generated a model with internal V-grooves and without

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Nomenclature

English symbol

A_1	Wetting cross section of the micro-channel
A_{cont}	Surface in contact with the liquid layer
A_{pipe}	Radial section of pipe
r_c	Effective of equivalent capillary radius in the direction of interest
r_H	Hydraulic radius of the micro-channel
r_m	Radius of semicircular groove
g	Gravitational acceleration
R	Inner radius of pipe
p	Groove depth
w	Groove width
Q	Heating power
$\dot{m}_{evaporated}$	Certain mass of liquid
T_{sat}	Saturated temperature
T_{pipe}	Temperature of the inner surface
k_{pipe}	Conductivity of pipe
$c_{p,pipe}$	Specific heat of pipe at constant pressure
t	Time
q	Internal heat flux
st	Saturated temperature
kf	Kind of fluid
tg	Type of fluid

Greek symbol

θ	Angular liquid front position
v_1	Liquid front velocity
v_1'	New liquid front velocity
ρ_1	Density of liquid
μ_1	Dynamic viscosity of liquid
σ	Surface tension
β	Contact angle of the liquid–steam–solid interface
γ	Micro-channel angle to the vertical
Ø	Apex angle
δ	Thickness of the pipe
λ	Latent heat of evaporation
ξ'	Angular relative coordinate

other types of grooves, such as semicircular groove. Peterson also failed to investigate the effects of the different types of grooves and failed to examine the parameter designs of the contact angle of the liquid–steam–solid interface as well as the micro-channel angle of a pipe that is vertical to the governing equations. Additionally, Rojas [14] partially analyzed the above parameter designs [14]. On the other hand, Peterson and Rojas did not investigate the effects of saturated temperature, radius, fluids, microgrooves, and groove width on thermal behavior. Limited literature is available on the relationship among heat flux, liquid front velocity, liquid mass, groove width, and the establishment time of the highest heat flux. Previous studies did not provide design guidelines and instructions on heat-pipe grooves. Therefore, this study solves these issues and proposes designs and recommendations for the parabolic trough in solar thermal power plants.

2. Mathematical modeling

This section will develop the governing equations for fluid flow in pipe with microgrooves, and then a methodology to solve these equations which present accordingly to predict liquid front position. Next, predicting the maximum external heat flux in an open-grooved micro-channel of the heat pipe can withstand and maintain efficient heat transfer. Liquid front velocity was considered without heat flux (an adiabatic model) on the basis of the approach of Peterson [13]. A horizontal pipe with microgrooves etched in its inner surface is studied by using a stratified two-phase flow, as shown in Fig. 1.

Liquid travels upward in the x^* direction of the pipe because of capillary pressure in the microgroove. Therefore, the wet portion of the inner pipe surface increases, resulting in heat flux. We developed a model to forecast the behavior of saturated liquids under different operation temperatures and examined the relationship between heating power and the liquid mass.

The fluid dynamics of only one microgroove is considered because the behavior of thermal dynamics is similar or all microgrooves in the entire pipe. However, concerns regarding the two-phase flow still exist. Liquid moving in a microgroove displaces the steam in the microgroove. Thus, if steam-to-liquid resistance is negligible (e.g., the steam velocity related to the liquid is negligible, and the steam pressure is assumed constant in its definition domain [15]), then this resistance may be considered a single-phase flow [16]. This problem also emerges if a stratified two-phase flow exists inside the microgroove pipes. Thus, the flow characteristics in the micro-channel pipes are influenced only by the momentum balance of the liquid film in the direction of the liquid, such as the x^* direction (Fig. 1).

A milling machine manufactured the microgroove of the pipe, so the cross section is triangular with two important parameters, namely the depth of grooves (p) and the apex angle (Ø). Semicircular cross-sections were also created. These geometries result in the parameters in Eq. (2), which include r_H, r_c, A_1, A_{cont}, and A_{pipe} in Table 1.

Liquid front velocity is applied without heat flux [13]. The adiabatic model (without heat flux) considers an open micro-channel with the liquid layer as its control volume and the balance of forces as its momentum equation.

$$\text{Inertial force} = \text{capillary driving force} + \text{gravitational force} + \text{viscous force}. \quad (1)$$

Applying the results of Dung et al. [17], Eq. (1) becomes

$$\frac{dv_1}{d\theta} = \frac{1}{\rho_1\theta v_1}\left(\frac{2\sigma\cos\beta}{r_c} - \rho_1 gR(1-\cos\theta)\cos\gamma - \mu_1\frac{v_1}{r_H}\frac{A_{cont}}{A_1} - v_1^2\rho_1\right). \quad (2)$$

Table 1 denotes that the feature length governs the flow rate through the capillary system, and the effective capillary radius (r_c) is twice the hydraulic radius (r_H), which is similar to that of the capillary effect in porous media [15].

To reduce calculation errors regarding the maximum position of the liquid front, Eq. (2) is reformed by time t as an independent variable instead of as a liquid front position (θ). By considering the microgroove angle of the vertical γ and by assuming contact angle β to be equal to zero, we can produce new simultaneous equations.

$$\begin{cases} \dfrac{d\theta}{dt} = \dfrac{v_l}{R} \quad \text{(a)} \\ \theta\dfrac{dv_l}{dt} = \dfrac{2\sigma\cos\beta}{R\rho_l r_c} - g\cos\gamma\,(1-\cos\theta) \\ \quad -\mu_l\dfrac{v_l}{r_c/2}\dfrac{A_{cont}}{RA_l\rho_l} - \dfrac{v_l^2}{R} \quad \text{(b)} \end{cases} \quad (3)$$