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Entropy generation of supercritical water in a vertical tube with concentrated incident solar heat flux on one side

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ABSTRACT

This paper presents the results of a numerical investigation of entropy generation of supercritical water in a vertical tube with concentrated incident solar heat flux on one side. The characteristics of heat transfer and pressure drop in the tube are analyzed first. The decrease in shear stresses near the pseudo-critical region results in the decrease in turbulence production and the increase in friction factor. It is the common cause of heat transfer deterioration and an abrupt increase in pressure drop near the pseudo-critical region. Entropy generation mainly depends on the temperature gradient along the vertical tube's radial direction which is due to the thickness of the thermal boundary layer and the intensity of secondary flow. The results further show that entropy generation of supercritical water in a vertical tube with concentrated incident solar heat flux on one side decreases with increasing mass flux and decreasing incident heat flux. In addition, to balance the minimum irreversible losses and hydraulic resistance in the tube in a central receiver, the relationship between incident flux and mass flux is determined.

1. Introduction

To improve solar-to-electric conversion efficiency of concentrated solar power systems, many studies [1,2] have focused on developing central receivers with high temperature and high pressure. Concerning heat transfer fluids (HTF) through central receivers, molten salt and superheated steam have been currently used in commercial solar tower power plants [3]. Pressurized air, nano-fluids and supercritical water are under development for central receivers with high operating temperature to improve solar-to-electric conversion efficiency [3,4]. Compared with other HTF, supercritical water is more attractive due to such advantages as the elimination of the steam generator and reduction of costs. In previous work [4], the heat transfer to supercritical water in a vertical tube from a cavity-type central receiver with a tubular panel has been investigated. However, the numerical analysis in previous study is mainly based on the first law of thermodynamics, the understanding of the quality of energy from the central receiver is not given. To design and perform the thermodynamic optimization of the central receiver with supercritical water, entropy generation analysis [5–8] based on the second law of thermodynamics which has been widely used in the fields of thermal system is essential in this paper.

The entropy production analysis was introduced by Bejan [9]. After that it has been widely applied in the analysis and optimization of thermal systems as well as heat transfer and fluid flow problems. In the field of solar thermal collectors [10], this approach has been widely used to optimize the design processes and operation parameters of the collector. In Giangaspero's study [11], an application of the method of irreversible losses minimization to optimize the configuration of a solar heat exchange surfaces was presented; the irreversibility due to heat transfer and fluid friction was reduced by improving design process. Not only can method of irreversible losses minimization optimize the geometry of solar collector, but it also contributes to selecting the appropriate heat transfer fluids. The heat transfer characteristics and flow implementation of the different nanofluids in a flat plate solar collector have been theoretically investigated by Alim et al. [6]. The CuO nano-fluid was found to reduce the entropy generation and maximize the exergy efficiency. Moreover, the optimal operating strategy can be given on basis of the irreversible loss minimization, to ensure the minimum irreversibility due to heat transfer and fluid friction. Mwesigye [12,13] conducted a numerical analysis of the entropy generation in a parabolic trough receiver with thermal oil as the HTF at different inlet temperatures and flow rates. The results showed that at a given inlet temperature, a flow rate exists for which the entropy generation is a minimum.

Although some useful results about applications of the second law of thermodynamics in solar collectors have been achieved,

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Nomenclature

A	cross-sectional area, m^2
Be	Bejan number
c_p	specific heat, J/(kg °C)
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants in the ε equation
D	diameter, m
g	acceleration of gravity, m^2/s
G	mass flux, kg/(m^2·s)
h	heat transfer coefficient, kW/(m^2·K)
k	turbulent kinetic energy, m^2/s^2
K	secondary flow intensity
q	heat flux, kW/m^2
p	pressure, Pa
Pr_t	turbulent Prandtl number
r	radius of the tube, m
S_{gen}	volumetric entropy generation, kW/(m^3·K)
$S_{gen,F}$	volumetric entropy generation due to fluid friction, kW/(m^3·K)
$S_{gen,H}$	volumetric entropy generation due to heat transfer, kW/(m^3·K)
T	temperature, °C
u, v, w	velocity components in the x, y and z directions, m/s
x, y, z	axial direction, m

Greek symbol

α	circumferential angle, °
α_t	turbulent thermal diffusivity, m^2/s
ε	dissipation rate of k, m^2/s^3
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
μ_t	turbulent viscosity, Pa·s
μ_{eff}	effective viscosity, Pa·s
ρ	Density, kg/m^3
τ	shear stress, N/m^2

Subscript and superscript

b	bulk
in	incident, inside
out	outside

most previous works are found to be focused on the HTF with stable thermal–physical properties. Studies on the effect of the variation of fluid properties on the rate of entropy generation are scarce. Further, fluid viscosity [5,14] is usually considered as a single variable that varies mildly with temperature whereas the dependence of other thermal–physical properties to temperature is often considered negligible. According to Sahin [15], the effect of viscosity variation on both the irreversibility and the pumping power is considerable and the dependence of viscosity on the temperature cannot be neglected. For supercritical carbon dioxide with highly variable property in a vertical tube heated by uniform heat flux [16], the mechanisms of entropy generation were found to act differently in the near wall region compared to the region away from the wall. However, the mechanism of local entropy generation variations along the flow cross section was not described explicitly.

For supercritical water in a vertical tube heated by concentrated incident solar heat flux on one side, large variations in the thermal–physical properties of supercritical water in the pseudo-critical region and non-uniform heat flux on one side will inevitably lead to the changes both in the distribution of entropy generation and the contribution of each of the mechanism of irreversibility. There are two methods of accounting for entropy production in the post processing phase of a CFD solution for turbulent convective heat transfer problems: the direct method and indirect method [17]. The direct method is superior because researchers can get the information how the overall entropy production is distributed with it. And it can be applied to complex flow situation with large variations in the thermal–physical properties of fluid. Therefore, the direct method is used in this paper. Considering irreversibility is mainly due to heat transfer and fluid friction, the characteristics of heat transfer and the pressure drop caused by fluid friction of supercritical water in a single tube in a central receiver are studied in the current work first. Next, the mechanism of irreversible losses of a supercritical fluid in a tube heated by non-uniform heat flux and the effects of mass flux and incident flux are numerically investigated. In this paper, the results provide valuable information for the design processes and the operational parameters to improve the system efficiency of the central receiver using supercritical water.

2. Physical model

In this study, a cavity-type receiver with a tubular panel is considered as the solar tower receiver with supercritical water. For the cavity-type receiver, the concentrated incident solar heat flux is received on one side, the other side is thermally insulated. As a basic unit of the central receiver, a single vertical tube is taken as the object of study. Fig. 1(a) shows the schematic diagram of the calculation model. The tube receives the concentrated incident solar heat flux on the right half; the left half of circular tube is thermally insulated. The flow direction of supercritical water is upward. The calculation model is symmetric with respect to the x-axis. To simplify the calculation model and reduce the computational time, the up half circular tube is selected as the computational domain, as shown in Fig. 1 (b). The incident flux is located on the outside wall where α is less than 90°. The tube material is 316L stainless steel which has a thermal conductivity of 24.5 W/(m·K) [18]. The geometrical parameters for the single tube are shown in Table 1.

Fig. 2 gives the typical variations of the property of water at the supercritical pressure of 24.5 MPa, the proposed operating pressure for the central receiver which is often used in the supercritical water cooled reactors [19]. NIST REFPROP software [20] is used to calculate the thermal–physical properties of water. The most significant changes in the properties occur within ±25 °C from the pseudo-critical temperature of 383 °C. Near the pseudo-critical line, the special heat shows a sharp peak. The viscosity, density and thermal conductivity decrease dramatically in this region.

3. Numerical analysis

3.1. Governing equations

The governing equations for steady-state include the continuity, momentum and energy equations. The continuity equation is given as follows:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$