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Heat transfer to supercritical water in a vertical tube with concentrated incident solar heat flux on one side

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ABSTRACT

A solar tower power plant with supercritical water as a heat-transfer medium in the central receiver is potentially one of the most promising solar thermal power technologies due to its high solar-to-electric efficiency. In this paper, the heat transfer of supercritical water in a vertical tube of a solar tower receiver has been investigated. A 3D mathematical model has been developed to investigate the distribution of heat flux in the circumferential direction of a circular tube heated by concentrated incident solar flux on one side. The RNG k–ε model with the standard wall function is employed to describe the turbulent flow of water from a liquid-like state to a gas-like state, and the results are validated with experimental data. For supercritical water in a tube heated on one side by concentrated incident solar heat flux, the maximum wall temperature is located on the sunward outside wall where the incident heat flux is at a maximum. In the pseudo-critical flow region, due to the drastic turbulent diffusion of supercritical water, the temperature distribution of the supercritical water in the tube is evenly distributed at the same flow cross section. To avoid deterioration in the heat transfer of supercritical water, the relation between the threshold incident solar heat flux and mass flux for the supercritical water has been provided. Furthermore, the Nusselt correlation which can be used to predict heat transfer coefficient of the vertical tube heated non-uniformly on one side by concentrated solar flux has been confirmed.

1. Introduction

Solar tower power plants receive much attention due to their high solar-to-electric efficiency [1,2] which results from an increasing in the allowable incident heat flux and power cycle efficiency with increasing working temperature. In solar tower power plants, the central receivers have high solar-thermal conversion efficiencies with high acceptable incident heat flux [3]. Indeed, the central receivers, which generally employ either molten nitrate salt or water/steam as the heat transfer fluid, have improved at increasing the acceptable incident heat flux since the 1980s [4]. The receivers using water/steam in Solar One and CESA-1 promise an incident flux of 300 kW/m^2; the molten salt solar receiver from Solar Two allows a peak flux of 800 kW/m^2. Increasing the allowable incident heat flux is not only helpful for improving the solar-thermal conversion efficiency but also for reducing the Levelized Energy Cost (LEC) from concentrating solar power technologies.

Furthermore, the currently operating solar tower power plants mainly operate in subcritical Rankine power cycle with gross thermal-to-electric efficiencies between 30% and 40%. Considering the applications of cycle working fluids with increasing working temperature in coal fired power plants [5] and nuclear power plants [6], the concept of a central receiver with supercritical heat transport fluids [7] has been proposed, and the feasibility of this method has been theoretically demonstrated. The corresponding advantages include high power cycle efficiency, elimination of the steam generator, reduction of costs and so on. In 2014, the world's first prototype of a solar tower with a supercritical water central receiver successfully produced supercritical steam at a pressure of 23.5 MPa and temperature of 570 °C in Australia. However, further detailed reports are not available. Taking into account the promising applications of supercritical water in solar thermal tower powers in the future, a cavity-type central receiver with supercritical water is proposed and its performance is studied in this paper.

Unlike the central receivers with molten nitrate salt or subcritical water/steam, the tubes of a central receiver with supercritical water should have the relatively small diameters due to the high pressure and high temperature [8]. The sunward side of the tubes

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Nomenclature

A, B, C	constant
c_p	specific heat, J/kg °C
$\overline{c_p}$	average specific heat, J/kg °C
D	diameter, m
G	mass flux, kg/m^2 s
g	acceleration of gravity, m^2/s
Gr	Grashof number
$\overline{Gr}$	average Grashof number
h	heat transfer coefficient, kW/m^2 K
n	number
q	heat flux, kW/m^2
Re	Reynolds number
r	radius of the tube, m
T	temperature, °C
x, y, z	axial direction

Greek symbol

α	circumferential angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
$\overline{\rho}$	average density, kg/m^3

Subscript and superscript

ave	average
b	bulk
in	incident, inside
out	outside
pc	pseudo-critica
w	wall

is used to absorb the concentrated solar energy and transfer the energy to the heat transfer fluid passing the tubes. The incident flux focuses on one side of the receiver tube, and the other side of tube is thermally insulated. Therefore, there is a non-uniform flux distribution on the outside tube surfaces. Generally, the concentrated incident heat flux is regarded to be a uniform and parallel arrangement, a cosine distribution [2] on the sunward side is assumed. The heat transfer to supercritical water in a tube heated by concentrated incident solar heat flux on one side has to be studied to develop a solar tower power with a supercritical water central receiver.

Due to the large variations in the thermal–physical properties of supercritical water in the pseudo-critical region, unusual heat transfer behavior (heat transfer enhancement or heat transfer deterioration) occurs in this region. Therefore, extensive experimental and modeling research [8–10] on heat transfer of supercritical water has been conducted since the 1950s, mainly involving supercritical water as coolants in nuclear power plants. These investigations have revealed that the characteristics of heat transfer in supercritical water is strongly affected by heat flux, mass flux, flow direction and buoyancy. Based on these studies, various empirical heat transfer correlations/look-up tables [11,12] have been developed. These empirical methods are well validated within their own applicable ranges and can adequately predict the heat transfer coefficient of supercritical water when buoyancy effects are negligible or slight. In simulations [8,9,13], the reliability of the turbulence model is evaluated to exactly predict the characteristics of heat transfer in supercritical water, including Standard k–ε, RNG k–ε, SST k–ω, Realizable k–ε and so on. However, most studies focus on heat transfer in a circular tube heated by uniform heat flux in the circular direction. For the single-side uniform heat flux distribution on the water wall in a supercritical fossil-fired boiler, Li [14] discussed the flow and heat transfer mechanisms using the numerical method. The results revealed that the buoyancy effect is much less significant for single-side uniform heating without quantitative results. Further, the heat flux into the tube in the conventional boiler is uniform based on the one side tube surface. Different from the heat flux for heat exchanger tube in nuclear power plants and the tube used in boilers, the heat flux around the tube is non-uniform in a cosine distribution on the sunward side due to the uniform incident flux and parallel arrangement. To date, to the best knowledge of the authors, there are limited data available for supercritical water in a tube heated on one side by concentrated incident flux. Therefore, it is valuable to investigate the heat transfer behavior of supercritical water in a circular tube heated by incident flux on one side.

The objective of the present communication is to investigate the characteristics of the heat transfer of supercritical water in a vertical tube heated non-uniformly on one side by concentrated solar flux. To obtain more detail about the distribution of non-uniform heat flux in the circumferential direction of a vertical tube, a 3D simulation is utilized. The RNG k–ε model with the standard wall function is employed to carry out numerical simulations. The model is validated by comparing the results to experimental data. The effect of incident flux and mass flux on the heat transfer of supercritical water is studied. Furthermore, the buoyancy criterion, onset of heat transfer deterioration and Nusselt correlation of heat transfer under incident solar heat flux are also investigated in this paper.

2. Modeling

2.1. Physical properties of supercritical water

In this article, the inlet pressure of the vertical tube is 24.5 MPa, the bulk temperatures of supercritical water range from 337 to 540 °C. Because the pressure drop inside the circular tube is relatively small compared to the proposed operating pressure for supercritical water in the tube, only the effect of temperature on the supercritical water's physical properties at 24.5 MPa is considered for the simulation. NIST REFPROP software [15] is applied to calculate the water properties. Fig. 1 gives the property variations of water at 24.5 MPa based on NIST REFPROP. At 24.5 MPa, the pseudo-critical temperature is 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. In addition to the pseudo-critical region, other regions are labeled as the liquid-like region and gas-like region.

2.2. Geometry and distribution of heat flux

A cavity-type receiver with a tubular panel is considered for the supercritical water solar tower receiver. Fig. 2 shows the cross section of the calculation model. To simplify the calculation model, a half circular tube is selected as the computational domain in this study. The tubular panel receives the concentrated radiation on the right half and converts it into available thermal energy in the supercritical water, the left half of circular tube is thermally insulated. The tube material is 316L stainless steel. Because the change in the thermal conductivity of 316L stainless steel in the temperature range of 300–600 °C is very small [16], the value of