Numerical simulation study on the heat transfer characteristics of the tube receiver of the solar thermal power tower

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ABSTRACT

In a solar thermal power tower system, a molten salt tube receiver is a significant component. However, the tube flow performance is different with other tubes, half the circumference of the tube is heated with a different heat flux and half that circumference is insulated. As the properties of molten salt change with the temperature along the alloy tube wall, the distributions of temperature and heat flux and the heat transfer characteristics are very complex. The present study uses the computational fluid dynamics to reveal these phenomena. The results show that the temperature distribution of molten salt and tube wall are very uneven whether in an axial or radial direction, and the temperature of the inner tube wall is an important parameter for preventing the decomposition of molten salt. The heat flux of the heating surface increases with the increase of velocity; however, the situation is just the opposite for the adiabatic surface. The heat transfer coefficient is higher as compared with the Sieder–Tate equation. The value of the local Nu number is almost unchanged with the change of the cosine angle over all circumferential direction.

1. Introduction

Solar thermal power plants generate electric power from sunlight by focusing concentrated solar radiation to heat transfer fluid to produce heat energy, and then change it to electricity in a conventional generator. It is another higher potential solar power technology except photovoltaic system. The types of solar thermal power plants are power tower plants, parabolic troughs and dish engine plants [1–4].

A solar power tower plant uses a field of sun-tracking mirrors, called heliostats, to concentrate sunlight onto a tower-mounted, centrally located receiver, where the thermal energy is collected in a heated fluid and then the high temperature fluid is transferred to the steam generator on the ground through pipes to produce high pressure and super-heated steam to power a conventional, high-efficiency steam turbine to produce electricity [5]. The solar power tower has the advantages of a higher ratio of focusing light, higher working temperature and longer lifetime etc. In the commercial application aspects, the external cylindrical receiver with molten salt as the heat transfer medium has high efficiency, greater power and low technical risk. The system has large heat storage capability and can generate electric power with continuity and stability. At the beginning of the 1980's, the first power tower system – Solar One was established in Southern California of the US. For Solar One, water-steam was chosen as the heat transport medium, producing 10 megawatts of power. The idea was to pump water up to the receiver to make steam, which was then brought down to the base of the tower to generate electricity or to thermally charge an enormous holding tank containing oil, rock, and sand. In 1996, Solar One was reconstructed to Solar Two after improvement in the storage system in order to demonstrate advanced molten-salt power tower technology [6].

The cylindrical receiver is one of the key components for the solar power system. It consisted of 24 panels arranged in a cylinder in Solar Two [7]. Each panel incorporated 32 thin-walled tubes with end-bends connected to manifolds on each end of the panel. According to the design requirement, the velocity of molten salt was controlled in order to keep the inlet temperature 288 °C and the outlet temperature 565 °C.

Although many countries have built stable solar power tower stations [8], there are few reports about the heat transfer characteristics of the tube receiver that is different with normal situation because of the special heating method with semi-circumference heated and semi-circumference adiabatic. Naphon [9] investigated the heat transfer and flow characteristics of the horizontal spiral-coil tube by numerical and experimental methods. Hot and cold water were used as working fluids. Reasonable agreement was

obtained from the comparison between the results from the experiment and those obtained from the model. Nevertheless, the results was based on the average value of the whole tube, it cannot shows the local heat transfer characteristics. Wu [10] conducted the experimental study on the heat transfer characteristics of molten salt in a circular tube and found a good agreement between the experimental data of molten salt and the well-known correlations presented by Hausen and Gnielinski respectively. However, the heat transfer performance with uneven heat flux was not analyzed because of some difficulties in experiment.

In actual solar thermal power, because of the different concentrated solar radiation and different incident angle, the heat transfer is uneven along the circumference. The local temperature, heat flux and heat transfer coefficient of the tube receiver need to be obtained when the solar plant operates normally. Since the solar receiver is composed of many same single tubes, in this study, the heat transfer characteristics of a single molten salt tube receiver with asymmetric heat flux around the tube is simulated numerically. The numerical simulation results of this paper shows the special distribution of the temperature and heat flux, at the same time the special heat transfer characteristics are obtained whether on a whole or local viewpoint. The results will provide references for the design of the whole tube size, the control of temperature and the heat transfer analysis etc.

2. Physical model

The physical model of a single tube receiver is shown in Fig. 1. The length between the tube inlet and outlet is 1 m, the tube's outer diameter is 20 mm and the thickness of the tube is 2 mm. One side of tube called the heating surface receives heat flux from the solar radiation, and the other side is called adiabatic surface covered with heat insulator. Fig. 2 shows the heat flux on the heating surface in accordance with the cosine function $q(\theta) = q_{net} \cdot \cos\theta (-90^0 \leqslant \theta \leqslant 90^0)$. The molten salt flows into the inlet, absorbs heat to increase the temperature and then flows out of the outlet. Since the physical properties of molten salt will vary with temperature, this study considers the effects of the variable properties of molten salt. The specific density and dynamic viscosity of molten salt can be referenced to the chart in the literature [11], however the thermal conductivity and specific heat capacity are supposed to be constant 0.571 W/m K and 1510 J/kg °C respectively. This study considers the impact of wall heat conduction on heat transfer. Alloy 625 is selected as the material of the tube receiver, with the density 8440 kg/m^3, the thermal
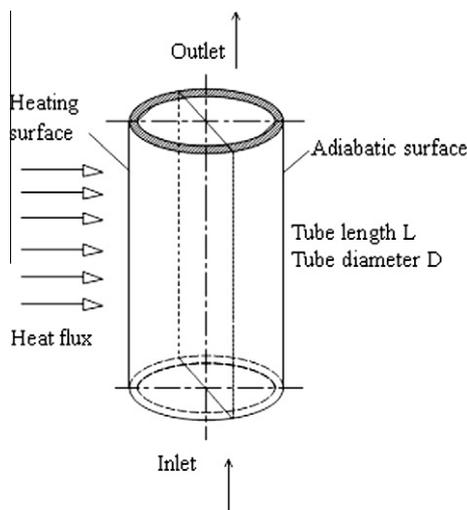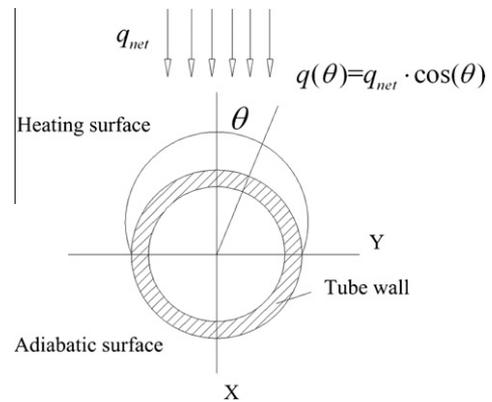
conductivity 16.3 W/m·K, and specific heat capacity 505 J/kg °C. Alloy 625 is a Nickel–Chromium alloy used for its high strength, excellent fabricability and outstanding corrosion resistance during the temperature range from cryogenic to 1093 °C. Alloy 625 is an important research direction for molten salt receiver material in the future.

The commercial CFD software Fluent 6.2 is used to simulate the heat transfer process. The Gambit mesh is structured grid, creating 8 faces and 2 bodies. The boundary definitions are VELOCITY INLET for inlet boundary, OUTFLOW for outlet boundary, WALL for other boundaries, FLUID for molten salt in the tube, and SOLID for tube wall separately. The equations for solving and controlling are continuity equation, N-S momentum equation and energy equation for three-dimensional compressible flow. The equations are solved by discrete solver, k–epsilon turbulence model, the SIMPLE algorithm for the pressure–velocity coupling, and second-order upwind format for the pressure and momentum. The turbulence dissipation rate, turbulent kinetic energy, and energy all use the QUICK format.

3. Analysis of the results and discussion

3.1. The comparison of numerical and experimental data

Verification of the Fluent setup was done by comparing the numerical data with experimental data. Fig. 3 is the schematic diagram of experimental system, including molten salt tank, pump, molten salt furnace, electrical heater, tube receiver and data acquisition system etc. The experiments used composite nitrate salt as heat transfer fluid. The molten salt was heated by the molten salt tank and furnace to specified temperature, flowed to the testing
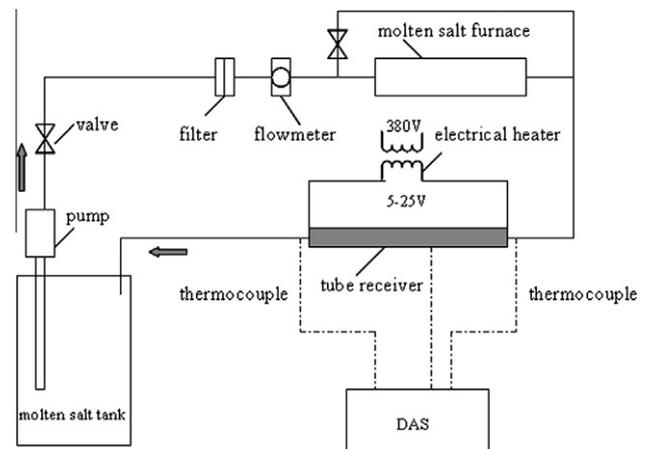

Fig. 2. Heat flux distribution scheme along the circumference direction.

Fig. 1. Three-dimensional model of single tube receiver.

Fig. 3. The schematic diagram of experimental system.