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Research paper

Experimental study on the heat transfer characteristics of a low melting point salt in a parabolic trough solar collector system

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HIGHLIGHTS

- A low melting point molten salt was applied in CSP systems.
- Experiment indicates a low risk of freezing and plugging.
- The results show the proportion of the thermal loss at the joints.
- Total heat transfer coefficient of the water-to-salt heat exchanger was obtained.

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ABSTRACT

An experimental system of parabolic trough solar collector and heat transfer was set up with a new molten salt employed as the heat transfer medium (with a melting point of 86 °C and a working temperature upper limit of 550 °C). The circulation of molten salts in the system took place over 1000 h. Experiments were conducted to obtain the heat loss of the Heat Collector Element (HCE), the total heat transfer coefficient of the water-to-salt heat exchanger, and the convective heat transfer coefficients for the low melting point molten salt in a circular tube. The results show that the thermal loss of the tested HCE is higher than that of the PTR70, and the thermal loss at the joints of the collector tube represents about 5% of the total loss in the entire tube. The total heat transfer coefficient of the water-to-salt heat exchanger was between 600 and 1200 $W/(m^2 \cdot k)$ in the ranges of $10{,}000 < Re < 21{,}000$ and $9.5 < Pr < 12.2$. The experimental data show good agreement with existing well-known correlations presented by the Sieder-Tate equation and the Gnielinski equation. This experimental study on heat loss from molten salt flow in a receiver tube will hopefully serve as a helpful reference for applications in parabolic trough systems.

1. Introduction

Nowadays, concentrated solar power (CSP) presents tremendous potential for the large-scale deployment of clean renewable energy [1], and it has been proven to be the most mature solar thermal technology available. As a result, most construction projects for commercial solar thermal power plants are currently based on this type of collector [2–4]. Many different kinds of working fluids are used in CSP systems [5–7], and selecting the appropriate heat transfer fluid and storage medium is a key technological issue for the future success of CSP technology. Molten salt represents an extremely promising medium for heat transfer and storage in CSP plants; its advantages include a wide working temperature range, low vapor pressure, large heat capacity, low viscosity, good chemical stability, and low cost [8–11]. Molten salt CSP storage was shown to be commercially viable in 2008, when the 50MWe Andasol-1 plant with 7.5 h of molten salt storage began its operation [12]. However, the only CSP system that uses molten salt as the medium of heat transfer is the Archimede parabolic trough plant in Italy. In the Archimede system, the working fluid of the heat transfer and heat storage is solar salt that is a mixture of $NaNO_3$ and KNO_3 [13] with a high melting point (220 °C). In such systems, the cost of operation will rise dramatically if there is an unexpected drop in temperature in the operating process in which the salt is used as the heat transfer fluid. Therefore, additional hard-ware

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must be installed, such as heat tracing, insulation, or emergency water-dilution systems. The high melting point is a major disadvantage of conventional molten salts and limits their application in trough CSP systems [3].

Based on different mixing ratios of KNO_3–$NaNO_3$–$LiNO_3$–$Ca(NO_3)_2 \cdot 4H_2O$, a new kind of nitrate salt was developed by our research group. Experimental results have shown that the melting point of this molten salt can be as low as 86 °C with a decomposition temperature above 600 °C [14]. Previous experiments have been carried out to obtain the convective heat transfer coefficients of the turbulent flow and transition flows of Hitec salts, $LiNO_3$, and fluoride salts in a circular tube [15–20]. However, heat transfer performance using a low melting point salt has not been reported in the literature.

A parabolic trough solar collector and heat transfer system was constructed at the end of 2011 with a low melting point molten salt [14]. Since then, numerous engineering issues have been addressed, such as the plugging of solidified molten salt, charging and discharging methods, equipment selection, and thermal and flow parameter measurements. A series of experiments on low melting point molten salt were conducted in the trough solar collector and heat transfer system, and the results of the experiments are reported in this paper. The heat loss of the HCE and the convective heat transfer coefficients of turbulent flows were obtained in a circular tube, and the total heat transfer coefficient of the water-to-salt heat exchanger was obtained as well.

2. Description of experimental system and working fluids

2.1. Experimental apparatus

A schematic diagram of the experimental system is shown in Fig. 1. The system contains molten salt circulation and water circulation. The main parts of the two cycles include a molten salt tank, a high-temperature molten salt pump, a molten salt heater, a concentrating collector, a water-to-salt heat exchanger, a water cooler, a water heater, a mass flow meter, and a water pump. The characteristics of the collector are presented in Table 1.

Table 1
Characteristics of the parabolic trough collector.

Parameter	Value
Aperture width	5.77 m
Collector length	12 m
Focal length	1.71 m
Mirror reflectivity	90%
Geometric concentration ratio	82
Receiver material	Stainless steel 304L
Receiver external diameter	70 mm
Receiver inside diameter	66 mm
Outside glass envelope diameter	115 mm
Inside glass envelope diameter	109 mm
Wind load design basis	32 m/s

In order to avoid molten salt solidification in the tube, an automatic electric tracing band is utilized in the pipe system, the latter of which requires a certain lean of about 5‰. Due to the inherent properties of molten salts and the high temperature, most devices cannot effectively measure the molten salt flow. In order to measure the molten salt flow rates, many different types of flow meters were tested, such as target flow meters, mass flow meters, float flow meters, etc. Through comparative analysis, an ultrasonic flowmeter made by FLEXIM (Germany) was chosen to measure the flow rates of the molten salt, and a mass flow meter was installed in the water cycle. Meanwhile, the temperature of the molten salt was measured by a type K thermocouple with special limits of error (±1.1 °C or ±0.4% of the tested temperature, whichever is greater), and the temperature in the water cycle was measured with a PT100 resistance thermometer with an accuracy of 0.2 °C. To obtain different flow rates of the molten salt, a frequency converter was installed to control the molten salt pump. Before the molten salt was pumped from the storage tank to the pipeline, the entire molten salt flow loop had to warm up. When the molten salt in the storage tank was heated to a prescribed temperature by an electric heater, the molten salt pump started to circulate the molten salt in the salt cycle.

2.2. Working fluids

A new kind of low melting point molten salt prepared by our lab [14] with a melting point of 86°C and a working temperature upper limit of 550 °C was chosen as the working fluid in this experimental investigation. Its main thermophysical properties are listed in Table 2.

3. Results and discussion

3.1. Thermal loss of the HCE

In this parabolic trough solar system, the tested HCE features six evacuated collector tubes (each with a length of 2 m) welded together. Insulation with a length of 1.15 m and a thickness of

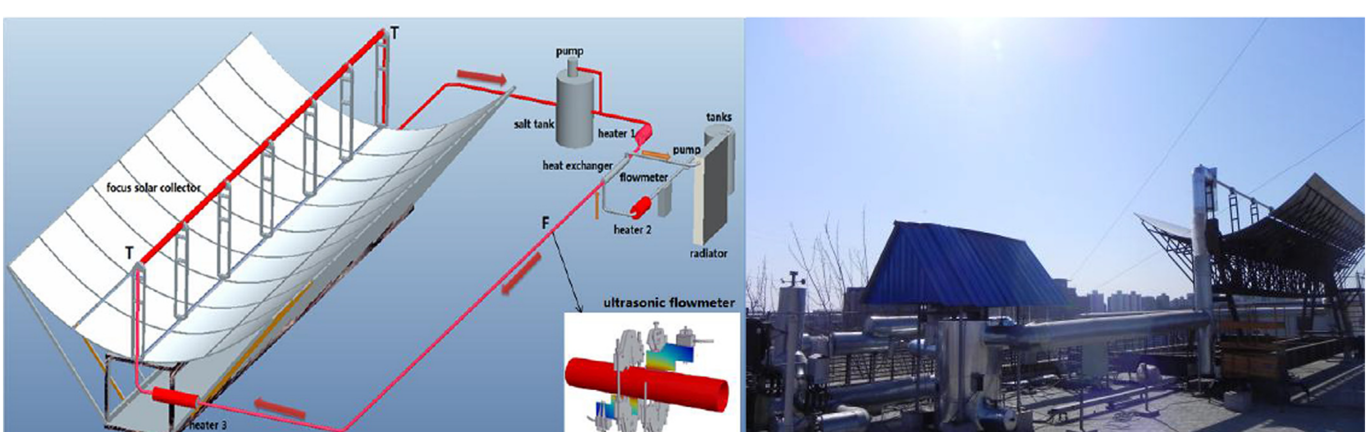

Fig. 1. Parabolic trough solar collector and heat transfer system with molten salt.