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A study on heat transfer characteristics of quinary molten salt mixture

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ABSTRACT

In this study, experimental analysis of the heat transfer characteristics of a quinary molten salt mixture was carried out. This mixture was developed at Korea Institute of Energy Research as a heat storage material for a solar thermal power plant. Experiments were conducted to obtain the heat transfer coefficient in a vertical tube and to generate steam in a heat exchanger. To obtain the heat transfer coefficient, the temperatures of the outer wall, inlet, and outlet were measured in upward molten salt flow. Heat transfer correlations were proposed for the molten salt based on experimental data. The accuracies of the correlations were 60% and 88% for the transition and turbulent flow regions, respectively, with an error range of ±20%. A concentric heat exchanger was used for steam production to use the molten salt for power generation. Superheated steam at 100 bar and 400 °C was generated through heat transfer between the high temperature molten salt and water, with an efficiency of 81–91%.

1. Introduction

In a concentrated solar power (CSP) plant, concentrated solar energy generates heat to produce high temperatures. The heat absorbed by a solar receiver is transferred to molten salt, which is used as a working fluid and a heat storage medium. The first role of molten salt is to produce high-temperature and high-pressure steam for the working of a turbine. The second role of molten salt is to store thermal energy for use in the case of electric load fluctuation on a cloudy day or at night.

A CSP plant that uses a storage system may be categorized as an indirect system or a direct system. In an indirect storage system, such as the Andasol-1 plant in Granada, Spain [1], storage is decoupled from the heat transfer fluid (HTF) loop of the solar receiver via a heat exchanger. A parabolic trough concentrator is used in the plant to heat oil to a temperature of up to 393 °C. The oil is fed directly to an oil–steam heat exchanger to produce steam at 100 bar and 377 °C for power generation. The rest of the heat is transferred to molten salt at 386 °C for storage. In a direct storage system, such as the Gemasolar plant in Seville, Spain [2,3], molten salt in a solar tower simultaneously acts as an HTF and a storage medium. The molten salt is heated up to 565 °C and stored in a tank. To generate power, the molten salt from the storage tank is passed through a heat exchanger to produced steam at 100 bar and 535 °C.

Molten salt has good thermal stability at high temperatures. In addition, it is possible to raise the Rankine cycle efficiency of a steam turbine in a power block [4]. Therefore, Solar Salt, which is thermally stable at 600 °C, is used in most CSP storage plants. The freezing point of Solar Salt is approximately 220 °C; this is a major problem as the freezing of molten salt can cause damage to the pipes and pumps in the plant. Auxiliary heating systems are required to prevent the freezing of molten salt. Molten salts with lower freezing points, such as Hitec, Hitec XL, and multicomponent mixtures, with performances similar to Solar Salt have been developed to solve this problem [5–8]. A quinary molten salt mixture with a freezing temperature and thermal stability temperature of 85 °C and 600 °C, respectively, was developed at Korea Institute of Energy Research (KIER) [9]. The quinary molten salt has a wide operating temperature range than existing molten salts due to the low freezing point and the high stability temperature. For this reason, it is possible to reduce the capacity of the auxiliary heater to prevent freezing problems in the system. In addition, because of the energy density, it stores more heat in the same volume. However, due to the high viscosity, more pump power is required to meet turbulent flow conditions during heat exchange. The properties of the existing and developed molten salts at 300 °C are presented in Table 1.

As heat transfer and storage medium, molten salt have been successfully applied in the field of CSP plant. In the design and

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Nomenclature

c_p	specific heat, J/kg-K
d	diameter, m
D_h	inner hydraulic diameter of tube, m
I	current, A
k	thermal conductivity, W/m-K
l	length, m
$\dot{m}$	mass flow rate, kg/s
Pr	Prandtl number
q_{input}	input power, W
$\dot{q}$	rate of energy generation per unit volume, W/m^3
r	radius, m
Re	Reynolds number
T	temperature, °C
V	voltage, V
x	streamwise coordinate, m

Greek symbols

η	steam generator efficiency

Subscripts

HTF	heat transfer fluid
i	inner
in	inlet
o	outer
out	outlet
w/s	water and steam

Table 1
Physical properties of the existing and developed molten salts at 300 °C.

Property	Solar Salt	Hitec	Hitec XL	KIER
Freezing point (°C)	220	142	120	85
Stability temperature (°C)	600	535	500	600
Density (kg/m^3)	1,899	1,640	1,992	1,840
Viscosity (cp)	3.26	3.16	6.37	6.18
Specific heat (J/kg-°C)	1,495	1,560	1,447	1,823
Energy Density (kJ/m^3-°C)	2,839	2,558	2,882	3,354

analysis of heat exchangers such as receivers and steam generators, the convective heat transfer characteristics of molten salts are an important factor. Experimental studies have been conducted on the heat transfer performance of molten salts. According to Hoffman et al. [10,11], molten salt is suitable for exchanging heat to the system at high temperatures, such as industrial processes and nuclear reactor systems. Hoffman et al. studied the heat transfer characteristics of LiF–NaF–KF and Hitec in a horizontal tube and derived their respective convective heat transfer coefficients. Silverman et al. [12] analyzed the heat transfer characteristics of $LiF–BeF_2–ThF_2–UF_4$ and $NaBF_4–NaF$ in a horizontal forced convection loop for designing certain components for molten salt breeder reactors. According to Wu et al. [13], Lu et al. [17] and He et al. [18], mixed molten salts have been successfully applied in the field of concentrating solar power and nuclear power engineering as a heat transfer fluid of secondary coolants. Wu et al. studied heat transfer of Hitec and $LiNO_3$ in the range of transition and turbulence and derived convective heat transfer correlations with a higher accuracy through experimental date and reference data [14–16]. Lu et al. investigated the heat transfer performance of Hitec in a vertical annular duct within the range of transition and turbulence. He et al. showed that the heat transfer performance of Hitec in a tube bundle was superior to that in a circular tube.

In this study, experimental analysis of the heat transfer characteristics of a quinary molten salt mixture developed at KIER was carried out. A new convective heat transfer correlation suitable for molten salts was derived based on reference data and experimental data in a vertical tube and a horizontal tube. The accuracy of the correlation was verified through comparison with the Dittus and Boelter [14] correlation commonly used in turbulent flow in a circular tube and the Wu correlation derived from transition flow and turbulent flow of molten salts in a circular tube. In addition, based on the observed heat transfer characteristics, a concentric heat exchanger was designed and manufactured to produce steam at 100 bar and 400 °C. The steam thus generated could be used for increasing pressure gradually. Then, heat transfer efficiency was calculated using the measured temperature and mass flow rate.

2. Measurement of heat transfer characteristics

2.1. Experimental setup and procedure

An experimental facility was configured to observe the heat transfer characteristics of molten salt according to the inlet temperature, mass flow rate, and power supplied in a vertical tube, as illustrated in Fig. 1. The facility included a molten salt furnace, pump, test section, and heat exchanger. The storage capacity of the furnace was 30 kg, and the molten salt in the furnace could be melted and heated to the target temperature using an electric heater. Using the pump, the heated molten salt was maintained at a constant flow rate in the tube.

The quinary ($NaNO_3–NaNO_2–KNO_3–KNO_2–LINO_3$) molten salt mixture that was used as the HTF in the experiment had a wide operating-temperature range and good thermal stability. The properties of the quinary molten salt in the range of 200 to 500 °C are presented in Table 2.

As illustrated in Fig. 2, the outer diameter of the test section is 12.7 mm, the thickness is 1.24 mm, and the length is 1,100 mm (excluding the entrance region). To heat only the test section, a direct current (DC) of 45 V and 600 A was supplied to it. Then, k-type thermocouples were used to measure the inlet, outlet, and external wall temperatures of the test section. Eleven thermocouples were attached to the external wall using laser welding.

The heated molten salt in the test section was passed through a counterflow heat exchanger where its temperature decreased, and then, it was returned to the furnace. Water was passed through a tube with an inner diameter of 10.22 mm in the counterflow heat exchanger, and the molten salt was passed through an annular tube with an inner diameter of 15.75 mm. Then, k-type thermocouples were used to measure the inlet and outlet temperatures. After the experiments, an air compressor was used to remove the molten salt inside the experimental system for preventing the freezing phenomenon of molten salt. The supplied air was heated through a spiral tube heat exchanger inside the furnace and supplied to the system.

The speed of the pump was controlled by varying its input current frequency to change the mass flow rate of the molten salt. The heat supplied to the test section was controlled by the current of the DC power supply. The mass flow rate of the water supplied to the heat exchanger was adjusted through a valve, based on the outlet temperature of the molten salt. All pipes including those