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Research Paper

Thermal performances of molten salt steam generator

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HIGHLIGHTS

- Thermal performances of molten salt steam generator were experimentally studied.
- Overall heat transfer coefficient reached maximum with optimal molten salt flow rate.
- Energy efficiency first rose and then decreased with salt flow rate and temperature.
- Optimal molten salt flow rate and temperature existed for good thermal performance.
- High inlet water temperature benefited steam generating rate and energy efficiency.

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ABSTRACT

Molten salt steam generator is the key technology for thermal energy conversion from high temperature molten salt to steam, and it is used in solar thermal power station and molten salt reactor. A shell and tube type molten salt steam generator was set up, and its thermal performance and heat transfer mechanism were studied. As a coupling heat transfer process, molten salt steam generation is mainly affected by molten salt convective heat transfer and boiling heat transfer, while its energy efficiency is also affected by the heat loss. As molten salt temperature increased, the energy efficiency first rose with the increase of heat flow absorbed by water/steam, and then slightly decreased for large heat loss as the absorbed heat flow still rising. At very high molten salt temperature, the absorbed heat flow decreased as boiling heat transfer coefficient dropping, and then the energy efficiency quickly dropped. As the inlet water temperature increased, the boiling region in the steam generator remarkably expanded, and then the steam generation rate and energy efficiency both rose with the overall heat transfer coefficient increasing. As the molten salt flow rate increased, the wall temperature rose and the boiling heat transfer coefficient first increased and then decreased according to the boiling curve, so the overall heat transfer coefficient first increased and then decreased, and then the steam generation rate and energy efficiency of steam generator both had maxima.

1. Introduction

Molten salts [1,2] have been widely used as high temperature heat transfer and storage fluid in solar thermal plant, chemical engineering, nuclear heat source, and so on. Because steam is easy to be transported and used, it is widely used in power generation, chemical industry, food product and other industries. Molten salt steam generator is critical equipment for thermal energy conversion from molten salt to steam in solar thermal power station and molten salt reactor. During the molten salt steam generation process, high temperature thermal energy transfers from molten salt to water, and the water changes to steam by heat absorption. As a result, the molten salt steam generation is a coupling heat transfer process with molten salt convective heat transfer and boiling heat transfer.

Many researchers designed and investigated types of molten salt steam generator. Kinyon [3] designed a vapor generator organization in form of a shell and tube type heat exchanger for producing superheated vapor and particularly adapted for use of molten metal or molten salt as heating medium. Faugeras et al. [4] designed low temperature steam generator for a low-power nuclear reactor, and this steam generator consisted of a single enclosure containing a molten-salt reactor and a fluidized-bed exchanger. Vriesema [5] investigated molten salt steam generator using fluorides as heat transfer agents for power generation, and high pressure water was used to increase its boiling point above the freezing point of molten salt. Allman et al. [6] presented the

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})	λ	thermal conductivity (W m^{-1} K^{-1})
d	inner diameter of tube (m)	μ	viscosity (kg m^{-1} s^{-1})
K	overall heat transfer coefficient (W m^{-2} K^{-1})	η	energy efficiency (–)
h	the enthalpy (J kg^{-1})	σ	uncertainty (–)
l	length (m)		
n	number of tube (–)	*Subscripts*	
Q	heat flow (W)	ab	absorbed heat flow
q	heat flux (W m^{-2})	f	fluid
q_m	mass flow rate (kg/h)	in	inlet condition
q_v	volumetric flow rate (m^3/h)	inp	input heat flow
S	area (m^2)	out	outlet condition
T	temperature (°C)	w	water
Greek symbols			
ρ	density (kg m^{-3})		

design and testing of the steam generator subsystem (SGS) for the Molten Salt Electric Experiment (MSEE) at Sandia Laboratories in Albuquerque. Bechtel Corporation [7] reviewed and evaluated the steam generator and thermal storage tank designs for commercial nitrate salt technology. Zavoico [8] described the steam generator structure in solar power tower, and presented the inlet and outlet parameters for steam generator. Lu et al. [9] proposed the method and device for coiler molten salt steam generator. Gaggioli et al. [10] proposed an innovative concept of stratifying molten salt storage system with an integrated steam generator.

The thermal performance of molten salt steam generator was affected by the heat transfer of molten salt, and the convective heat transfer of molten salt in different configurations was investigated in available literature. Hoffman and Cohen [11] experimentally investigated the heat transfer of mixed molten salt $NaNO_2$–KNO_3–$NaNO_3$, and correlated associate convective heat transfer equations. Wu et al. [12,13] studied the forced convective heat transfer of molten salts in circular tube. Lu et al. [14,15] experimentally studied the convective heat transfer of molten salt in transversely grooved tube and spirally grooved tube, and found that the spirally grooved tube and transversely grooved tube can remarkably enhance the heat transfer of molten salt. Lu et al. [16] further measured the convective heat transfer of high temperature molten salt in a vertical annular duct. Xiao et al. [17] investigated the heat transfer characteristic of molten salt flow in helical annular duct. Rivas and Rojas [18] developed the shell-side heat transfer correlation of molten salts along helical-coil tube bundle steam generator.

From the last century, the heat transfer of flow boiling was investigated in detail. Rohsenow [19] developed a method of correlating heat transfer data for surface boiling of liquids. Thom et al. [20] studied boiling in subcooled water during flow up heated tubes or annuli. Fang et al. [21] reviewed and developed heat transfer correlation for saturated flow boiling of water. Santini et al. [22] studied flow boiling heat transfer in a helically coiled steam generator for nuclear power applications.

Till now, types of molten salt steam generator were designed, and the molten salt convective heat transfer and flow boiling heat transfer have been separately studied, while the thermal performance of the whole molten salt steam generator as a coupling heat transfer process was seldom reported. In this paper, experimental measurements were conducted to investigate the heat transfer of molten salt steam generator. The steam generation rate, overall heat transfer coefficient and energy efficiency of molten salt steam generator were further analyzed under different inlet flow rates and temperatures of molten salt and water. In addition, the maximum steam generation rate and energy efficiency of steam generator were further studied by considering the coupling effect of molten salt convective heat transfer and flow boiling.

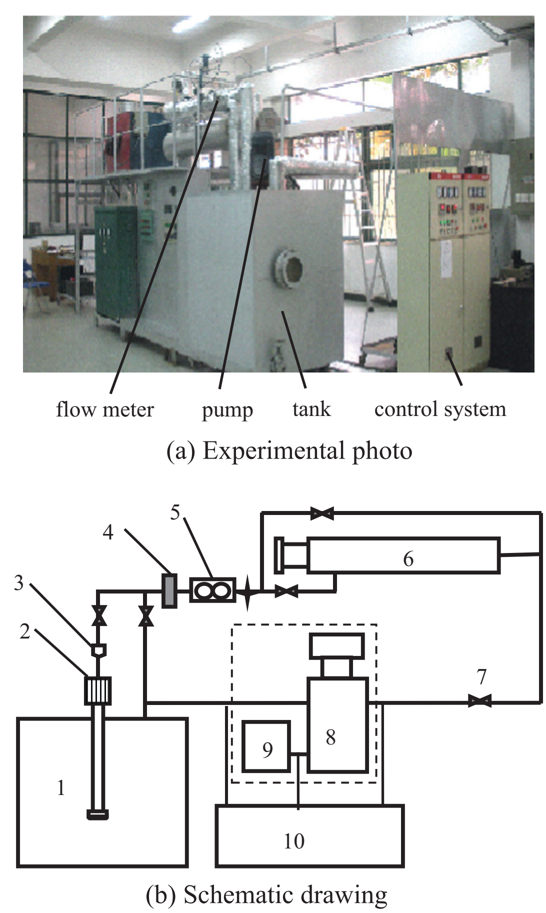

Fig. 1. Experimental system. 1. Molten salt tank, 2. pump, 3. pressure gauge, 4. filter, 5. flowmeter, 6. furnace, 7. valve, 8. steam generator, 9. water tank, 10. acquisition system.