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Experimental investigation of circular submerged jet impingement heat transfer with mixed molten salt

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ABSTRACT

In order to investigate the heat transfer characteristics of mixed molten salt, an experimental setup for the submerged jet impingement has been established in this paper. Firstly, an experimental investigation on heat transfer of submerged jet impingement with water as working fluid was carried out to verify reliability of experimental method. A good consistence was found between experimental results and those classical correlations from references for stagnation heat transfer, which indicate the reliability and accuracy of experimental method. On the basic of ensuring the reliability of experiment, a series of studies on jet impingement experiments were carried out with new mixed molten salt. The results indicated that effect of submerged jet impingement heat transfer enhanced gradually with the increase Reynolds number and the heat transfer characteristics at the stagnation are analogous with the water in the scope of experimental investigations. Further, a correlation about quaternary mixed molten salt was proposed based on experimental data. At same Reynolds number, the Nusselt number of mixed molten salt is obviously higher than that of water at stagnation zone because of its higher Prandtl number and becomes lower than water at larger radial distance due to its higher viscosity. The results indicated that thermophysical properties of working fluid have an enormous influence on the Heat transfer performance. The experimental results in this paper provide a necessary technical guarantee for the study of heat transfer of the high temperature fluid.

1. Introduction

In recent years, water and thermal oil has been widely used as heat transfer fluid in Concentrating Solar Power (CSP) with the development of solar energy technology [1]. Concentrating Solar Power (CSP) technologies use mirrors to concentrate the sun's light energy and convert it into heat to create steam to drive a turbine that generates electrical power. In CSP systems, the water or thermal oil is heated from solar energy by solar collector to a higher temperature. Then, the solar energy is stored in water or thermal oil. The solar energy stored is utilized by heat exchanger to provide uninterruptedly heating、cooling and power generation. Although the water has a big specific heat capacity, its capacity of energy storage is limited because of its lower boiling temperature. If water is heated to a higher temperature, a higher running pressure will be necessary for the equipment and the risk from equipment will increase. Similarly, thermal oil has high costs, high running pressure, which limits the further improvement of the efficiency of solar thermal power generation. The thermal oil has not satisfied the demand of massive energy storage from the solar energy. It is well known that improving the working temperature of fluid is an effective method to store more energy. However, a higher pressure will be satisfied for equipment when the working temperature of fluid is improved. More investment on equipments will be needed, which is not conducive to large-scale energy storage and utilization. Besides, the efficiency of heat exchanger used in recovery and utilization of waste heat is lower when the working temperature of fluid is lower. So, high performance medium and a more effective way of heat transfer enhancement were demanded to improve the heat transfer efficiency on solar energy utilization and other energy utilization.

Molten salts as an ideal media of high-temperature heat transfer and heat storage have been receiving a great deal of attention due to the characters of a upper limit working temperature range (550 °C), large heat capacity, good chemical stability and a lower running pressure [3]. Molten salt has been utilized to store energy in the domain of battery、solar thermal power and so on. Presently, the binary and ternary molten salt have been used as the working fluid to store the solar energy in solar thermal power generation system [2,3]. More mixed molten salts, such as Solar salt、Hitec salt and quaternary mixed molten salt etc.

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Nomenclature

A	area of heated surface, m^2
d	inside diameter of the nozzle, m
Nu	local Nusselt number
q	volume flux, L/s
Q_v	heat flux, W/m^2
h	heat transfer coefficient, $W/(m^2{\cdot}K)$
Pr	Prandtl number
r	radial distance from stagnation point, m
R	electrical resistance
Re	Reynolds number
tf	target temperature, °C
tw	jet temperature, °C
u	velocity, m/s
z	distance from jet to impinging plate, m

Greek symbols

ρ	density kg/m^3
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, $kg/(m{\cdot}s^2)$

were developed and used as the heat transfer fluid to meet the requirement of industrial applications (including the molten salt battery、solar thermal power generation and biomass pyrolysis technology) [3–6]. Regarding molten salt as working fluid to replace the thermal oil not only can improve efficiency of solar thermal power generation [4], but also can reduce the running cost of solar thermal power generation system and reduce working pressure of heat collection and heat transfer system.

Ding et al. [7–9] conducted some experiments about the flow characteristics and viscosity of Hitec molten salt, whose results indicated that the Hitec salt had a better flow characteristics at higher temperature. Ren [10,11] provided thermophysical properties of quaternary mixed molten salts having a melting point 86 °C and a decomposition temperature above 600 °C. Wu et al. [13] made some researches about the forced convection heat transfer in circular pipe by utilizing new quaternary mixed molten salt and provided a formula of convective heat transfer. Chen et al. [14] provided numerical results about the mixed convection heat transfer in horizontal square tube by utilizing molten salt. Lu et al. [15] utilized the new quaternary mixed molten salt to make some researches about nature convective heat transfer, which indicated that the Nusselt number of molten salt was slight higher than that of water. However, it is found from references [12–15] that the heat transfer efficiency of forced convection heat transfer in circular pipe and nature convective heat transfer of molten salt is lower by comparing the relationship between Reynolds number and Nusselt number. Thus, some other methods of heat transfer enhancement also should be explored to improve heat transfer efficiency.

Jet impingement is an effective way that can generate a strong flow and heat transfer between fluid and heated surface [16,18], which has been used widely in industrial fields especially in cooling of gas turbine. Many researches about jet impingement heat transfer focused mainly on different fluids and the geometrical structure of jet [16–23]. Although the heat transfer characteristics of air, water, oil, and refrigerant have been studied with the method of jet impingement, the current researches about heat transfer of jet impingement focus mainly on the lower temperature range from 4 °C to 40 °C [16]. Importantly, it is rare to make a series of researches about heat transfer characteristics of jet impingement at the high temperature. It's pointed out by [17] that thermal properties of fluids play an important role in the aspect of convective heat transfer. With technology of jet impingement used widely, the effect of temperature on the thermophysical properties of working fluid is becoming more and more obvious. Although many different fluids have been studied with jet impingement, the heat transfer characteristics of molten salt have been not reported and verified in open references. Comparing with common fluids, molten salt has a larger heat capacity、a larger working temperature range、a better chemical stability、lower running pressure and a higher molting point. The viscosity of quaternary mixed molten salt is above 7.14 times as high as that of water. The maximum working temperature of quaternary molten salt can reach to 550 °C, which is beneficial to a large scale heat storage. The common fluids used in the area of jet impingement cannot run in higher temperature and in lower pressure. Molten salt materials are such high temperature phase-transition thermal storage materials to be most extensively adopted at present due to such virtues as high latent heat of phase transition, compatibility between the transformation point and the highest temperature of heat engine circulation. Therefore, making a research about heat transfer characteristics of mixed molten salt with the method of jet impingement will be beneficial to explore a method to improve the heat transfer efficiency of molten salt.

The aims of this paper are to investigate heat transfer characteristics of molten salt and explore an effective way of heat transfer

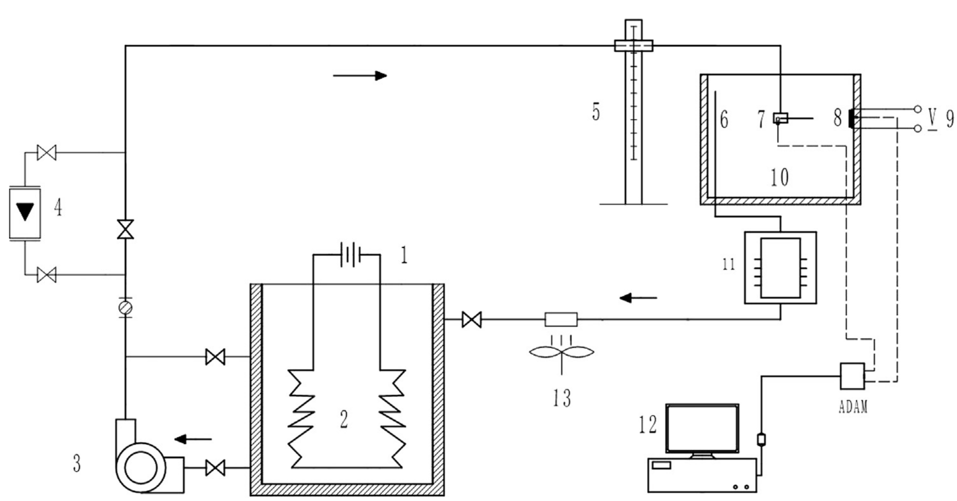

Fig. 1. Schematic diagram of experimental system for submerged jet impingement. 1. electric heater, 2. fluid reservoir, 3. gear pump, 4. rotating flow meter, 5. adjustable coordinate frame, 6. drain tube, 7. nozzle, 8. test section, 9. DC power, 10. test chamber, 11. self-made flow meter, 12. computer, 13 cooling fan.