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Experimental study of inlet structure on the discharging performance of a solar water storage tank

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ABSTRACT

The utilization of the solar water heating system can reduce the conventional energy consumption of a building. A good inlet of the solar storage tank can enhance the thermal stratification and improve the thermal storage efficiency and discharging efficiency. Experiments were carried out to investigate the discharging performance of a rectangular storage tank with different inlet structures which were slotting-type inlet, direct inlet and shower-type inlet. This study aimed to provide guidance for the optimization of the inlet structure of water tank so that the efficiency of solar water heating system (SWHS) could be improved further. The effective discharging efficiency and effective discharging time were introduced to evaluate the performance of water tank with different inlet structures. The results showed that the slotting-type inlet exhibited the best thermal stratification and improved the discharging performance of the tank more effectively than the other two inlets. Energy saving potential of new inlet was also presented.

1. Introduction

Solar energy plays an important role in reducing fossil energy used to maintain the indoor climate and domestic hot water supply [1]. Solar water heating system (SWHS) has been widely used all over the world [2]. Thermal energy storage (TES) is considered the best way to solve the problem that the supply and demand of thermal energy do not coincide in time, especially for solar energy. TES can make full use of solar energy and allow a smaller collector area. The TES also helps to maintain the stability and reliability of the energy supply system where the dynamical demand of energy occurs [3]. The storage tank is an important component of the SWHS and has great effect on the performance of the SWHS [4]. Improving the performance of SWHS reduces the auxiliary energy (e.g. electricity) used to heat the water, which is a large portion of the building energy consumption. Thermal stratification exists in the thermal storage tank and the improvement of the thermal stratification could improve the charging performance and discharging performance of thermal storage tank. The structure of the inlet has great effect on the thermal stratification in thermal storage tank [5,6]. The optimized design of the inlet could inhibit the turbulent mixing of the water and improve the thermal stratification in storage tank and therefore improve the performance of TES and SWHS as a result [7,8].

Ievers and Lin studied the turbulent mixing of cold and hot water inside the tank during discharging progress and found that the mixing of the inlet flow and water inside the tank was the most important factor to determine the thermal stratification [9]. Berkel and Hahne investigated the influence of the inlet and outlet structures on the thermal characteristic of the tank. The results indicated that the inlet and outlet design was the key factor of the formation of the thermal stratification and the optimized inlet and outlet structures could make the water flow in cylinder pattern flow style effectively so that the valuable energy of water in the tank could be utilized in maximum [10,11]. Shin et al. studied the mechanism of thermal stratification and optimized the design of the water tank in order to obtain the highest efficiency. A computer program based on Patankars SIMPLE algorithm was designed to compute fluid movement characteristics in water tank. Results showed that a higher efficiency could be obtained in a larger tank and a curved type diffuser exhibited better performance of thermal stratification compared to the flat plate-type diffuser [12]. Furthermore, Lavan and Thompson carried out experimental study on the temperature stratification in storage tank during discharging process and found that the location and geometry of the inlet port had greater influence on the achievement of stratification during the dynamic operation of the tank than the outlet [13]. Andersen and Furbo measured the effect of mixing between hot and cold water during the discharging progress in solar tanks with different inlets and analyzed the influence of mixing on the yearly thermal

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Nomenclature

V_{st} volume of water tank (m^3)
t_{use} unit replacement time (s)
t discharging time (s)
k number of data acquired
$T_{o\text{-}use}(\tau_{use})$ outlet water temperature at dimensionless time (°C)
$T_{o\text{-}use}(\tau_{use}=0)$ outlet water temperature at the initial time (°C)
m_j mass of each water layer (kg)
c_p specific heat capacity of water (4.18 kJ/(kg °C))
$T_{j\text{-}use}(\tau_{use}=0)$ temperature of each water layer at the initial time (°C)
$T_{i\text{-}use}$ inlet water temperature (°C)
$E_{st}(\tau_{use}=0)$ the total energy of water tank at the initial-time (kJ)
$E(\tau_{use})$ accumulated energy contained of outflow hot water (kJ)

Greek letters
ρ density of water (kg/m^3)
τ_{use} dimensionless discharging time
$\eta(\tau_{use})$ discharging efficiency
ν_{use} discharging flow rate (m^3/s)

performance of a solar domestic hot-water system under Danish weather conditions. They found that the yearly net utilized solar energy for the system with PEX pipe inlet decreased by as large as 23% compared with the system with half ball baffle inlet [14].

Altuntopt studied the effect of obstacle between inlet and outlet on thermal stratification in storage tank during discharging and the results showed that the obstacle could improve thermal stratification [15]. Alizadeh experimentally investigated the effect of inlet temperature and inlet structure on the discharging efficiency. The results indicated that the inlet with a downward conical tube on top improved the discharging efficiency significantly [16]. Zachar studied the effect of different size of the plates situated opposite to the inlet and found that the diameter of the plate and the distance between the plate and the top of the inlet had a significant effect on the temperature stratification during discharging [17]. It will always be an interesting subject for scientists and engineers to improve the discharging performance of solar storage tank by using simple and effective way.

To analyze the stratification effect and the discharging performance different methods were applied by researchers. Dehghan and Barzegar studied the performance of the mantle tank with initially stratification in simulation. The low Reynolds number k–ω model was utilized and the results showed that the Grashof number, Reynolds number and inlet/outlet opening size had an impact on the thermal stratification obviously [18]. A. Castell et al. studied various dimensionless parameters including the Richardson number, mix number, discharging efficiency, Reynolds number and Peclet number to evaluate the thermal stratification through 24 set of experiments. The results indicated that the Richardson number and discharging efficiency could effectively evaluate the thermal stratification in the storage tank [19]. Ghajar and Zurigat investigated the effect of inlet geometries on thermal stratification in a thermal storage tank numerically and the Richardson number was introduced to analyze the performance of the tank. The results showed that when the Richardson numbers above 10, the effect of inlet geometry on the thermal stratification was negligible [20]. Wang and his colleagues summarized the development of

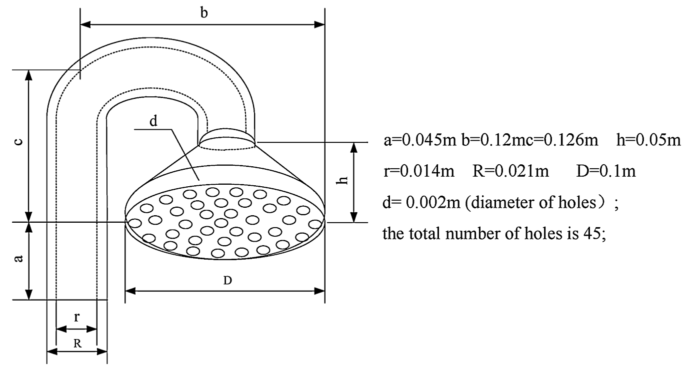

Fig. 1. Structure of the shower-type inlet.

the thermal stratification in detail and compared the destruction factors and evaluation index of the thermal stratification [21].

In this study, the experimental investigations of three simple inlet structures including slotting-type inlet, shower-type inlet and traditional direct inlet in solar water storage tank were carried out in discharging process. The effective discharging efficiency and effective discharging time were introduced to evaluate the performance of water tank with different inlet structures. The optimization of inlet has been proposed to improve the performance of discharging of water tank.

2. Experimental set-up

The experiment system was designed to study the performance of storage tank with different inlet structures. A water tank with dimensions of 0.8 m (height) × 0.4 m (width) × 0.4 m (length) was built and the top lid of the tank could be disassembled so that the inlets could be changed easily. The outside of the tank was insulated by foam insulation with thickness of 0.03 m. Three inlet structures including slotting-type inlet, direct inlet and shower-type inlet were installed in the water tank respectively to study the influence of different inlet structures on the discharging performance of the tank. The different inlet structures were shown in Figs. 1–3.

Schematic diagram of experimental system was shown in Fig. 4. The inlet and outlet of the tank were installed at the bottom and top cover of the tank respectively. Before the experiment, the water in the tank was heated to 60 °C by the electric heater and then pumped into the tank from the top so that the water temperature inside the tank could remain evenly and constant. Inlet water was supplied from the mains of city water during experiments. The flow rate was measured by glass rotor flow meter and the accuracy of the flow meter was 1.5%.

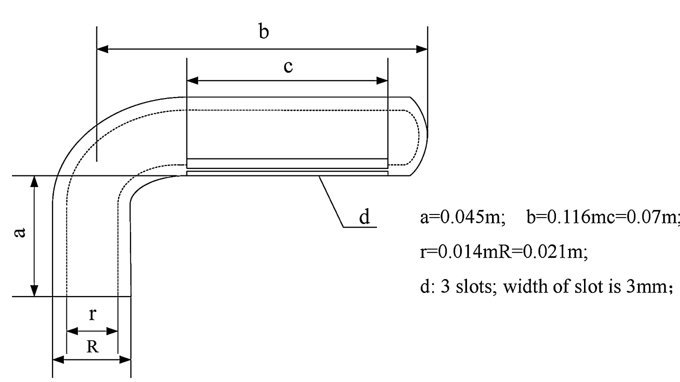

Fig. 2. Structure of the slotting-type inlet.