Journal of Energy Storage 15 (2018) 124–132

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Experimental study on destruction of thermal stratification tank in solar collector performance

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A R T I C L E I N F O

Article history:
Received 30 June 2017
Received in revised form 23 September 2017
Accepted 4 November 2017
Available online 13 November 2017

Keywords:
Collector efficiency
Solar water heating
Thermal energy storage
Thermal stratification
Water mixing
Water storage tank

A B S T R A C T

Destructing thermal stratification of water storage tank and effect on solar collector performance was investigated experimentally. First experiment was performed using conventional thermosyphon flow of water. In the second experiment, without discharging the hot water storage tank of the previous day, the experiment was continued. Third and fourth experiments were started with similar condition to the first case. However, in the third case during the experiment, the tank's water mixed using a circulating pump and in the fourth case, fresh water was replaced at three different times with the same amount from tank's water. Results indicated lowering the temperature of the lower layers in the tank would enhance the solar collector performance. Collector performed accordingly from best to worst; the three times tank discharge, conventional, water flow circulation, and initially charged tank recharge. For example, at 16:00, the collector's efficiencies for three-time tank discharge, normal, and destruction of thermal stratification experiments were 52.9%, 38.3%, and 32%, respectively. Further, at 17:00, the collector's efficiency for three-time discharge indicated 36% while nearly zero for other experiments was obtained. In addition, for heat absorption and collector's efficiency study, the theoretical results compared with the experimental results.

1. Introduction

Solar energy is one of the abundant and free energy on earth. It is the most available renewable resources that may be used especially in remote areas where access to energy is too difficult, e.g. using solar energy to obtain electricity for home has shown significant impacts on poverty reduction and social development in impoverished rural areas [1,2]. One of the easiest and least expensive ways to use solar energy is using solar water heaters that can be used to supply hot water of bath [3]. In Barbados, which is located in the eastern Caribbean, in order to eliminate dependency on the fossil fuels, the national strategic plan was designed for 2005–2025. In the proposed scheme, about 54,000 water heaters should be installed by 2025 [4]. Nowadays, remarkable advances have been made in solar hot water systems [5]. Furthermore, due to the increasing price of fuel, solar water heaters have a high potential in this regard [6].

Given the importance of solar water heaters, due to their simplicity and low cost, many researchers have been concentrating on designing and operating the most efficient system. Therefore, the design and better operation of the thermal stratification in the storage tank of solar water heaters is one of those areas of research. Storage tanks with thermal stratification are widely used in solar domestic hot water systems. In such systems, the hot water remains separated from the cold water by means of buoyancy forces [7]. Because of thermal stratification due to temperature effect on density, the lowest temperature occurs at the bottom layers in the tank. Therefore, thermal stratification through adjustment of inlet temperature for solar collectors plays an important role in the energy efficiency of collector [8]. Dinçer and Rosen [9] reported most comprehensive review of solar energy storages. It was confirmed the possibility of natural separation of hot and cold water in thermal energy storage tanks due to lower conductive heat transfer of water for separating hot and cold water. Hence, many experimental and theoretical activities have been conducted in an attempt to study the thermal stratification in tanks. Lavan and Thompson [10] performed some experiments to optimize design parameters including water inlet location, the effect of mass flow rate, and diameter of inlet and outlet ports of the tank. Alizadeh [11] studied the thermal behavior of a cylinder storage tank in different modes by numerical and experimental methods. Two different types of 1D numerical model precisely

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https://doi.org/10.1016/j.est.2017.11.004
2352-152X/

Nomenclature

A_c	collector area, m^2
A_p	collector gross area, m^2
C_p	specific heat of water, J/kg °C
C_c	circumference of collector gross area, m
F_R	collector heat removal factor
F'	collector efficiency factor
h_w	wind heat transfer coefficient, W/m^2K
I_T	instantaneous/hourly flux incident on top cover of collector, W/m^2
k_i	thermal conductivity of coefficient of insulation, W/m K
L_1	length of absorber plate, m
L_2	width of absorber plate, m
L_3	height of flat plate collector casing, m
δ	uncertainty
δ_s	thickness of side insulation, m
$\dot{m}$	mass flow rate, kg/s
N	number of transparent covers
Q	energy, W
T	temperature, K
T_{amb}	ambient temperature, K
T_{pm}	mean plate temperature, K
U_b	bottom loss coefficient, W/m^2K
U_L	overall loss coefficient, W/m^2K
U_S	side loss coefficient, W/m^2K
U_t	top loss coefficient, W/m^2K
V_∞	free stream wind speed, m/s

Greek symbols

δ	uncertainty
δ_s	thickness of side insulation, m
ε_g	emissivity of cover for long wavelength radiation
ε_p	emissivity of absorber for long wavelength radiation
η	efficiency of the collector
$(\tau\alpha)_{ave}$	average value of transmissivity-absorptivity product for beam and diffuse radiation

subscript

b	bottom
c	collector
exp	experimental
i	inlet
o	outlet
t	theory
u	useful
1	first experiment
2	second experiment
3	third experiment
4	fourth experiment

controlled the test results. Numerical results were shown to be in good agreement with the experimental, especially for top parts of the tank. Kenjo and Inard [8] developed a numerical model for shell tank, using a shell model approach.

The main advantage of shell model approach is its higher speed of computation than computational fluid dynamics (CFD) model. Thermal stratification in shell tank of the solar domestic hot water system was modeled by a satisfactory accuracy of 7% by shell model.

In newer approaches, simple pipes with a circular cross section were used to improve the thermal stratification in the tank. Andersen et al. [12] performed an experimental and theoretical study on three different types of pipes to improve thermal stratification in a hot water storage tank. Two types of volume flow rates in thermosyphon and force circulation systems were studied these stratification pipes. These studies showed the advantages and disadvantages of stratification pipes under practical operating conditions.

Goppert et al. [13] developed a new simple computation method for stratification pipes of solar storage tanks. This method was compared with CFD modeling. Studies indicated that the new method is in good agreement with a very higher computational speed than CFD. Brown and Lai [14] investigated the effectiveness of a porous manifold in the formation and maintenance of thermal stratification in a liquid storage tank. The porous manifold using a rolled tube-shaped, was able to reduce mixing of fluid layers with different temperatures, and thus was able to promote and maintain a stable stratification.

Diffusers were used to avoid the undesirable effects of fluid flow into and out of the tank on thermal stratification. Zachár et al. [15] numerically analyzed the impact of plates for thermal stratification inside a storage tank. They evaluated the effect of different plate sizes located at the inlet to enhance the thermal stratification of the tank. Chung et al. [16] studied new diffuser configuration to improve the performance of thermal storage tank. This configuration was tested by 3D transient numerical simulation. Reynolds number of the parameter was dominant in the range of studied parameters, and this configuration played an important role in the thermally stratified storage tanks. Rhee et al. [17] investigated thermal diodes by using four hot water storage tanks, three of them having thermal diodes with different arrangements. The greatest stratification was shown with a unique thermal diode arrangement named the express-elevator diode configuration. Çomaklı et al. [18] performed several experiments in order to assess the effect of the storage tank size in solar heating systems on the performance and applicability of solar hot water systems. They proposed a transient model using Matlab simulation for a hot water system under weather conditions of Erzurum, Turkey. Results indicated that by increasing the volume of storage tank, the collector efficiency increased. However, the temperature of available tank water reduced. Gasque et al. [19] analyzed the influence of thermal conductivity of inner lining material in a hot water tank on its thermal stratification during charging and stand-by periods. This was a numerical analysis conducted using 3D, CFD model. The obtained results confirmed that weak conductivity of inner lining materials helped the energy storage and thermal stratification of water during charge and subsequently during stand-by periods. Yaïci et al. [20] preformed 3D CFD simulation for improving functional and geometrical factors. They used 3D transient simulations for enhancing the performance of thermal storage tank. Further, by using transient CFD simulation, Ievers and Lin [21] performed a numerical evaluation regarding the effect of several parameters including the mass flow rate of inflow and changing the ratio of height to diameter of a vertical cylindrical tank. Their results indicated improved stratification and higher efficiency of the system by increasing the height to diameter ratio and reducing the inflow rate.

In state of the art solar water heaters, to access permanent hot water with suitable temperature in the absence of sunlight or in cases of the increased load of hot water consumption, other auxiliary energies like electricity and gas are used accompanied by solar energy. In remote areas where auxiliary energies are not accessible, fossil fuels are utilized to provide required hot water. Therefore, if the efficiency of solar hot water systems could be raised, a reduction in the consumption of fossil fuels will occur. To find a way to solve this problem, a simultaneous study has been conducted on the solar collector's efficiency and its effect on the thermal stratification of tank. So far, extensive research has been