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Original article

Numerical and experimental study of inlet-outlet locations effect in horizontal storage tank of solar water heater

Mohammad Reza Assari[a,*], Hassan Basirat Tabrizi[b], Morteza Savadkohy[a]

[a] Department of Mechanical Engineering, Jundi-Shapur University of Technology, Dezful, Iran
[b] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

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ABSTRACT

A good thermal stratification in the storage tank of the solar water heater is an effective process to increase the efficiency of the solar system. This study investigates numerically and experimentally the effect of varying the inlet and outlet location of the fluid in the horizontal cylindrical storage tank for optimizing the thermal stratification process. While the location of the outlet fixed, the inlet was varied and vice versa. A model based on an energy balance was introduced. Simulated temperature profile for each case was compared with the experiment, which indicated maximum deviation of up to 7%. In an experimental case at 1 p.m., the three average temperatures on the vertical line in the middle of the tank recorded 49.9, 48.7, and 48.4 °C with an average of 49 °C while the simulation result was obtained 47.1 °C. Hence, the experimental and numerical temperature difference of 1.9 °C with the error 3.9% was noticed. An appropriate location for the hot water inlet resulted in better thermal stratification in the storage tank. In addition, an appropriate location for the cold water outlet resulted a better collector efficiency, which both increased the performance of solar water heater system.

Introduction

Heating by using solar energy has significant benefits, especially in the regions with good source of solar radiation. Due to environmental pollution problems related to fossil fuels, application of solar systems, including solar water heaters has increased significantly. Solar water heaters absorb solar radiation energy, during the sunny hours, and to store it for reuse is very important. An efficient way of using a storage tank could be one of the main parts for saving energy. These tanks have a significant role in storing and utilizing solar energy. Most kinds of energy storage systems store in form of latent heat or sensible heat. Every ideal heat saving process is consisted of three stages: charging, storing, and discharging. Therefore, after generating energy, it is important to store it [1].

Nowadays, sensible heat storage tanks usually are common, and use water as a storage medium. Water, because of its availability and non-toxicity and having special properties such as high heat capacity, is one of the most appropriate energy storage media. The water in the storage tank of a solar water heater stores the radiation energy. In order to use thermosyphon and free convection principle, in a solar thermosyphon system, collector is placed in a lower level than storage tank. With sun's exposure to the collector surface, the water inside the tubes would be heated, then expands, becomes lighter than cold water, moves up the collector with natural movement, then enters to the reservoir. The force of gravity reduces the reservoir's cold water and the cold water moves toward the collector's inlet. The cold water enters the collector, forcing the hot water into the collector and up to the collector's exit pipe. In the storage tank, the hot fluid moves upward due to its lower density and the heavy cold fluid is placed in lower layers and thermal layers are formed.

Whenever the cold water supply is mixed with the hot water of the storage tank, the outlet temperature of the water heater, and as a result, the useful collected energy of the system is decreased. Thus, the mixing of the cold and hot water decreases the efficiency of the system. If a stable thermal stratification in the tank were created, the unfavorable effect of this mixing would be minimized. An appropriate heat storage tank should be stratified. That is, separates two different temperature fluids, and even at charge and discharge, the mixing of two fluids, is minimized. In addition, the effective storage capacity should be that the volume of in active fluid in the tank be minimized. The lower the heat transfers from the tank, the higher the system efficiency. The natural thermal stratification of storage tanks is because of the warmer fluid, due to its low density, freely moves up. That is why, in comparison with other types of tanks, the volume of these tanks is less, and the volume of their inactive fluid is low, and their efficiency is high [2].

The heat energy storage tank, in which the fluid is stratified in

* Corresponding author.
E-mail address: assari@jsu.ac.ir (M.R. Assari).

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Nomenclature

A	collector area (m^2)
CFD	computational fluid dynamics
C_P	specific heat (J/kg·K)
d	inlet/outlet diameter (m)
D	diameter (m)
E	total energy (J)
F_R	collector heat removal factor
g	gravitational acceleration (m/s^2)
H	height (m)
I	intensity of solar radiation (W/m^2)
k_{eff}	effective heat conduction coefficient (W/m·K)
L	length (m)
m	mass flow rate of fluid through the collector (kg/s)
p	pressure (Pa)
P	corrected pressure (Pa)
P_k	turbulence of viscous forces
$P_{\varepsilon b}$, P_{kb}	effect of buoyancy force
RNG	re-normalization group turbulence model
t	time (s)
T	temperature (K)
T_i, T_a, T_o	inlet fluid temperature, ambient temperature, collector average temperature (°C)
u_i, u_j, u_k	velocities (m/s)
U_L	collector overall heat loss coefficient ($W/m^2{\cdot}K$)
x_i, x_j, x_k	axes of coordinates (m)
X, Y, Z	axes of coordinates (m)

Greek Symbols

α	absorption coefficient of plate
β	heat expansion coefficient (1/K)
δ_{ij}	Kronecker delta
ε	turbulence loss rate (m^2/s^3)
η	collector efficiency
k	turbulence kinetic energy on mass unit (m^2/s^2)
μ	dynamic viscosity (kg/m·s)
ρ	density (kg/m^3)
τ	transmission coefficient of glazing
$(\tau_{ij})_{eff}$	declination stress tensor

different layers, has been the subject of many theoretical and experimental studies. Brumleve [3] confirmed to separate hot and cold water in a tank; it is applicable to use the phenomenon of natural separation of hot and cold water in heat storage tanks. He illustrated the advantages of thermal stratification in the form of calculations comparing stratified and mixed storage under conditions of fixed return temperatures from the load and from the collector. Lavan and Thompson [4] experimentally studied the effect of geometrical parameters and different operational conditions, such as geometry of inlet, magnitude of inlet mass flow rate, ratio of tank height to its diameter, and difference of inlet temperature and initial temperature of fluid in the tank. Their studies showed that every increase in the ratio of height to diameter, in the difference of inlet temperature and initial temperature of the fluid in the tank, and increase in inlet diameter, improves the thermal stratification in the tank. Influence of locating a plate in front of inlet flow of a vertical storage tank, on formation of different heat layers, was numerically studied by Zachár et al. [5]. It was found that plate diameter had little impact on thermal stratification in the middle of the tank but moving the vicinity of the plate diameter had a greater influence on thermal stratification. Alizadeh [6] studied thermal stratification in a horizontal storage tank experimentally and numerically for several cases. In the first case, the temperature of the water in the tank was uniform and higher than the inlet cold water temperature. In the second case, the tank at the beginning was stratified and the inlet cold water temperature was equal to the temperature of the water in the bottom of the tank. In the third case, the tank was stratified and the inlet cold water temperature was less than the temperature of the water in the bottom of the tank. The experimental results indicated that a slight improvement in thermal stratification in the tank has been achieved in the third set of experiments when the tank was stratified and the inlet cold water temperature was less than the temperature of the water in the bottom of the tank. Kenjo et al. [7] used a solar domestic hot water system with a mantle tank to study the thermal stratification in the storage tank. In three tests corresponding to the three inlet levels of the fluid into the mantle, inlet at the higher, middle and lower levels, the results show that in the first test the thermal stratification in the tank is much better than the rest. In addition, they found that experimental and numerical results differ by 6%.

Ievers and Lin [8] numerically investigated the influence of several parameters, such as the magnitude of the inlet mass flow rate and the ratio of height to diameter of a vertical cylindrical tank, using Fluent software. The results showed; whenever the ratio of height to diameter of tank and the magnitude of the inlet mass flow rate decrease the stratification improve. The numerical study by Gao et al. [9] on a horizontal cylindrical storage tank filled with hot water showed the improvement of the heat stratification, because of the inlet cold water velocity of the tank.

Since, the influence of changing inlet and outlet location of the fluid of a solar absorber to a horizontal cylindrical storage tank on the thermal stratification in the tank has not been reported; therefore, this study investigates such effect both numerically and experimentally. To perform the experiments, a thermosyphon solar water heater system with horizontal storage tank and integrated collector was used. Numerical simulation of thermal stratification in horizontal storage tank was performed using three-dimensional computational fluid dynamics (CFD) model. Section "Numerical modeling" is dedicated to numerical modeling of the problem including the physical model, problem hypotheses, governing equations with the RNG k-ε turbulent modeling, and validation. In Section "Description of the model experiment", the description of the experimental apparatus, how to conduct experiments, the thermocouple positions, and the type of the sensors are discussed. Section "Results and discussion" provides the results of the numerical simulation in modes of entering hot water into the reservoir and the flow of cold water from the reservoir towards the collector and the comparison with the experiments are shown. The conclusion follows in Section "Conclusion", which summarizes the effect of hot water inlet and cold water outlet on thermal layering and collector efficiency. The result of this research provides insight into optimal storage design and improving thermal stratification in the storage tank of the solar water heater, which is an effective process to increase the efficiency of the solar collector system.

Numerical modeling

Physical model

Physical model of the used hot water storage tank is shown in Fig. 1. The dimensions of the cylindrical tank are length 1000 mm and diameter 450 mm. This tank has an inlet port and an outlet port, with equal diameter of 15 mm. The storage tank is set as horizontal, and is filled with cold water. The starting temperature of water in tank is 293 K. Hot water enters to tank with temperature of 333 K. Velocity and temperature of the inlet water in the tank, at all time, is considered constant. Computation domain and meshing have been created and