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Original article

Towards an energy efficiency optimization of solar horizontal storage tanks and circulation pipes integrating evacuated tube collectors through CFD parametric studies

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ABSTRACT

This paper aims to simulate heat generation in two devices, namely the horizontal thermal storage tank and the circulation pipe, which are considered as the main devices constituting solar water heating systems. For this purpose, two dimensional simulations were performed, so as to numerically investigate the proposed configurations. The storage tank and the circulation pipe were considered as a partial discrete heating sources, while the other parts were maintained constantly adiabatic. The heat pipes are located at the tank's bottom wall where an isothermal temperature or a heat flux conditions are applied. Moreover, parametric studies regarding the geometry of the heat pipes were carried out. Three cases were studied: circular, rectangular and triangular configurations. A Prandtl number equal to 7 was used for the simulated case studies. The used equations were also described under detailed assumptions. Isotherms and average temperature evolutions were presented for various configurations in order to provide the achieved results. The storage tank and the circulation pipe were optimized and the energy transfer between the solar collector and the storage tank unit were maximized. Increasing the heat pipe's number and varying their shape could affect the mean time required to heat the stored water inside the horizontal storage tank. It is found that the rectangular shape of the heat pipe is the most effective due to its large heat exchange area, and would heat water to a temperature of 45 °C during 10 h, if the configuration of 6 heat pipes arrangement was used. While the required time to heat water to a temperature of 55 °C is 12.5 h using the configuration of 10 heat pipes arrangement. Besides, in order to achieve the maximal performance of the circulation pipe, the water inlet and outlet must be located respectively at the bottom and at the top to take advantage of the heated water's stratification.

Introduction

Nowadays, strong efforts have been made in attempt to either integrate or replace conventional energy sources with renewable energy sources in order to meet power requirements [1,2]. This is achieved thanks to the fact that renewable energy sources are non-depletable and non-polluting, while they also have low operation and maintenance costs, thus making them potential sources of alternative energy [2,3]. Solar water heating systems (SWHS) are among the favorable renewable energy and the most common systems because the use of these systems can result in high energy savings. However, limiting factors must be taken into account when using SWHS like economic viability, thermal performance and unpredictable behavior because the energy produced from renewable energy sources may not always meet the need [4].

It is necessary to investigate techniques to overcome these problems and to increase the viability of SWHS. A common solution to these defects is the utilization of an effective thermal energy storage system i.e. one that is able to store thermal energy at the highest possible temperature whilst exhibiting minimal thermal losses. The main thermal energy storage solutions include: thermally stratified storage and reversible chemical heat storage [5]. The second way, conducted in the present paper, involves to an optimization study on the design of equipment throws significant energy loss as the storage tank and circulation pipe in order to increase the rate of energy transfer, thereby maximizing the energy transfer from the solar collector to the energy

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Nomenclature

C_p	specific heat capacity [J/K.kg]
d	diameter of circulation pipe [m]
D	diameter of the tank [m]
g	gravitational acceleration [m/s^2]
h	width of the heat source for circulation pipe [m]
H	width for storage tank [m]
k	thermal conductivity [W/K.m]
Pr	Prandtl number
q	thermal heat [W/m^2]
Q_{in}	inlet mass flow rate [kg/s]
Q_{out}	outlet mass flow rate [kg/s]
T	temperature [K]
T_{in}	initial temperature [K]
T_m	reference temperature [K]
Ra	Rayleigh number
u	horizontal velocity [m/s]
v	vertical velocity [m/s]

Greek symbols

ρ	fluid density [kg/m^3]
β	thermal expansion coeffcient [1/K]
μ	dynamic viscosity [Pa.s]
α	thermal diffusivity [m^2/s]

Abbreviations

CFD	Computational Fluid Dynamics
CFL	Courant–Friedrichs–Lewy

storage units.

Thermal energy storage in water tanks is of a high importance in many engineering practicing in particular solar water heating systems. The operation process of the water tank can be divided into the dynamic mode of operation and the static mode of operation. The dynamic mode of operation refers to its operation when thermal energy from the tank is being used, i.e., when the discharging/charging process is taking place. The static mode of operation refers to its thermal behavior when the water in the tank is not being used, i.e., when there is not water flowing in/from the tank [6].

The static operation mode is also called the cooling process in some literature, because the thermal behavior in the static mode of operation is caused by a natural cooling process (i.e a passive mode) owing to heat losses to the surronding [7]. During the static mode of operation, velocity and temperature boundary layers form along the lateral wall of the water tank, as a result of the heat transfer from the fluid in the tank to the environment, thus inducing thermal stratification in the tank. This stratification significantly impacts thermal energy storage capacity and even system efficiency [8].

Many researchers interested in the topic of energy saving inside the storage tank. Jordan et al. [9] have worked on thermal stratification in small solar domestic storage tanks caused by draw-offs. They have compared storage tanks with different cold water inlet devices for small Solar Domestic Hot Water (SDHW) systems in order to reveal the impact of the cold water inlet device on the thermal stratification in two marketed tanks and to evaluate the possible enhancement in the annual system performance of small solar heating systems. To carry out system simulations, a multi-node storage model was used and expanded by an additional input variable to model the mixing behaviour depending on the operating conditions. They increase the solar fraction of about 1–3%-points in annual system simulations with a solar fraction of about 60% and fairly large domestic hot water flow rates.

Erdemir et al. [10] have investigated the thermal stratification of vertical mantled hot water tank with four different obstacles. It was found that placing the obstacle inside the inner tank in vertical mantled hot water tanks has improved thermal stratification of the tank. The best thermal stratification was obtained between $Y = 200$ and $Y = 300$ mm the distance from the tank bottom. Gandhi et al. [11] have investigated the temperature and flow patterns in centrally heated cylindrical tank. Effect of passive devices (aspect ratio, draft tube and fins) on stratification. Conducting fins of suitable size with its appropriate locations severely reduces mixing time and stratification. They have carried out flow (using particle image velocimetry) and temperature (using thermocouples) measurements in a rectangular tank ($0.8 \times 0.6 \times 0.6$ m^3) fitted with a central tube (forming the heat transfer surface). They have examined the effects of various internals in order to reduce the stratification. From the analysis, they conclude that they are able to estimate the size, velocity and energy distribution of turbulent structures. The detailed knowledge was employed in surface renewal type of theories for the estimation of rates of heat transfer. A good agreement was observed between the predicted and the experimental values of heat transfer coefficient.

GarcíMarí et al. [12] have developed a new inlet device that enhance thermal stratification during charging in a hot water storage tank. They have compared the effect of two water inlet devices in a hot water storage tank during a thermal charge process: a sintered bronze conical diffuser (SBCD) and a conventional inlet elbow (E). They have based on the evolution of the temperature recorded by the thermocouples, the 1-MIX number, as well as the thermocline evolution and other related parameters (shape, thickness and height of midpoint) in order to quantify the performance of the stratification. They conclude that the use of the SBCD for the hot water inlet favours thermal stratification of the water, regardless of the flow tested.

Fan et al. [13] have presented a numerical investigations of thermal stratification in a vertical cylindrical hot water tank established by standby heat loss from the tank. Parametric studies are carried out using the validated models to investigate its effect on thermal stratification of the tank by the downward flow and the corresponding upward flow in the central parts of the tank. Effects of tank volume, H/D ratio, insulation, initial conditions determined are investigated. Based on results of the parametric studies, a generalized equation for the heat loss removal factor is obtained by regression which takes into account the effects of different parameters. The equation was implemented in an existing tank optimization and design program for calculation of thermal performance of a hot water tank.

Göppert et al. [14] have introduced a new and much simpler computation method for stratification pipes of solar storage tanks making the determination of the individual fluid flows and the estimation of the effects of constructive changes possible. The comparison with CFD gives a qualitatively good agreement for a simple charge system. They discussed the results of a constructive modification of the charge system reducing the sucking effect. Moreover, Ievers et al. [15] have numerically simulated seven three-dimensional models by using the computational fluid dynamics program Fluent with realistic boundary and initial conditions applied in order to analyze the effects of tank geometry and operating conditions on the thermal stratification within a storage tank. The obtained results show that increasing the tanks height/diameter aspect ratio, decreasing inlet/outlet flow rates and moving the inlet/outlet to the outer extremities of the tank all result in increasing levels of thermal stratification.

Han et al. [16] have presented a survey of the various types of thermal stratification tanks and research methods and have introduced the reasons of energy storage with efficiency problems related to the applications and benefits offered by thermal stratification. Finally, they