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Experimental and simulated thermal stratification evaluation of an oil storage tank subjected to heat losses during charging

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HIGHLIGHTS

- Thermal stratification in an un-insulated oil storage tank is evaluated.
- Simulated results in good agreement with experimental results.
- Parametric results using model are presented.
- Effect of heat loss factor and ambient temperature on stratification is presented.

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ABSTRACT

Experimental and simulated quantitative thermal stratification evaluations of a small un-insulated oil storage tank subjected to heat losses during charging are presented. A model for simulating the thermal profile in the storage is developed. Simulated results using the model are found to be in reasonably good agreement with experimental results. The thermal gradients along the height of the storage are evaluated as function of the charging time. The thermal gradients are also evaluated as a function of the difference between the average temperature of the storage tank and the ambient surrounding temperature which signifies heat losses. The thermal gradient is seen to rise to a maximum value at some instance of time and then start to drop as thermal de-stratification in the storage tank starts. Parametric results using the model are also presented. The effect of the ambient temperature and the heat loss factor on the thermal gradient of the storage tank is investigated. Lower ambient temperatures and lower heat loss factors are found to increase the thermal gradient of the storage tank during the period when thermal stratification is increasing.

1. Introduction

Thermal stratification in solar storage tanks improves the overall efficiency of the storage tank. The increase in the efficiency is due to the fact that hotter fluid is delivered at the top of the tank while cooler fluid is delivered at the bottom resulting in a thermal gradient for a greater potential of thermal energy to be stored. Separation of the hot and cold regions in a storage tank occurs as a result of buoyancy forces during charging and discharging of the storage tank. As the storage tank is charged, the density of the hotter fluid at the top decreases, causing the fluid to rise to the top while the cooler fluid falls to the bottom. Various mechanisms result in thermal de-stratification which leads to a degradation in the thermal efficiency of the storage tank. Some of the major mechanisms which enhance de-stratification include heat losses to the surroundings, heat conduction between the cold and hot regions of the stored fluid, conduction along the tank wall and mixing of the fluid in the stratified layers during charging and discharging [1].

Various recent works have evaluated and quantified thermal stratification in domestic hot water (DHW) storage systems at temperatures below 80 °C [2–11]. Yee and Lai [2] studied the effects of a porous manifold on the thermal stratification of a solar DHW storage tank using a numerical model. The results obtained showed that heat losses and a porous tube with high thermal conductivity adversely reduced thermal stratification. An experimental study by Hegazy and Diab [3] on the performance of an improved design of a domestic water storage system showed that the improved design had a better discharging efficiency due to thermal stratification. Experimental and numerical investigations of vertical-mantle heat exchangers for solar DHW systems were done in [4]. Results showed that thermal stratification was destroyed at lower inlet temperatures of the mantle tank due to large recirculation of fluid. Haller et al. [5] carried out a literature review on different methods of determining thermal stratification

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Nomenclature

A_T	cross-sectional area of the storage, m^2
c_f	specific heat capacity of fluid, J kg^{-1} K^{-1}
D_T	diameter of storage tank, m
k_f	thermal conductivity of fluid, W m^{-1} K^{-1}
t	time, s
T_a	ambient temperature, K
T_f	fluid temperature, K
T_{in}	initial average temperature of segment, K
T_s	average temperature of a segment, K
U_T	heat loss factor, W K^{-1}
V_T	volume of storage tank, m^3
$\dot{V}_{chf}$	average charging volumetric flow-rate, ml/s
Y	height of storage tank, m
ρ_f	fluid density, kg m^{-3}

efficiency. Mondol et al. [6] carried an experimental thermal stratification evaluation of a novel heat exchanger for a solar hot water storage system. Results obtained indicated that the new design performed better than a traditional solar hot water storage system in terms of the heat gained from the solar collector. Hegazy [7] conducted experimentally an investigation on the effect of inlet design on the performance of storage-type domestic electric heaters. The slotted inlet design produced a better performance as compared to the other designs. An experimental analysis of a solar storage tank with open side inlets was carried out by Palacios et al. [8]. Modelling results were found to be in good agreement with experimental results. Castell et al. [9] experimentally compared dimensionless numbers to characterize thermal stratification. Their results concluded that the Richardson's number best described thermal stratification experimentally. A detailed literature review of thermal stratification within the water storage tank has been done in [10]. Different methods to evaluate thermal stratification as well as different designs to enhance thermal stratification were reviewed. Altuntop et al. [11] applied a validated numerical model to study the effect of obstacles on thermal stratification in a hot water storage tank. The obstacle types having gaps in the centers appeared to have better thermal stratification than those having gaps near the tank walls.

Other fluids (e.g. thermal oils) having higher operating temperatures than water can be used in thermal processes needing higher operating temperatures above the boiling point of water. Storage tanks using thermal oils are more viable if they are used for small domestic applications as small units. Small thermal oil storage tanks are relatively cheap and are comparable in price to small water storage tanks. Thermal oils also tend to stratify more naturally than water since the change in their densities with temperature is more pronounced as compared to water. Fewer papers on thermal stratification in other fluids other than water have been presented [12–18]. Oliveski et al. [12] presented a study on natural convection in an oil storage tank operating relatively at low temperatures. Experimental results were found to be in good agreement with numerical simulations. It was also demonstrated that the model was able to describe in detail the phenomena that occurs inside thermal tanks subjected to a natural convection regime. Mawire and McPherson [13] presented an experimental study of the controlled charging and thermal stratification evaluation of a combined oil/pebble-bed thermal energy storage (TES) system. Results obtained indicated various degree of thermal stratification. Mawire et al. [14] performed charging simulations for different solid pebbles for an oil/pebble-bed TES system. The amount of energy stored, exergy stored and the degree of thermal stratification were considered to be essential thermal performance parameters. A very small oil-in glass TES system was characterized experimentally for rapid heat transfer experiments [15]. Experimental results indicated an optimal charging flow-rate which was a compromise between achieving a greater heat transfer rate in the energy delivery device and achieving a greater degree of thermal stratification in the TES system. In a recent paper, Mawire and Taole [16] compared different experimental thermal stratification parameters for an oil/pebble-bed TES system. The temperature difference along the height of the storage tank and the stratification number were found to be adequate parameters to evaluate thermal stratification quantitatively. An oil storage tank under simultaneous charging and discharging was experimentally evaluated in [17]. Thermal stratification in the storage tank was evident for all the experimental cases investigated. Bruch et al. [18] presented an experimental and numerical investigation of a thermal oil dual-media thermocline for a concentrated solar power plant. Good agreement between experimental and numerical results was obtained for the thermal profile of the storage system.

Parameters which tend to reduce thermal stratification are very important since they tend to reduce the efficiency of the TES system. Heat loss to the environment is one important parameter and limited work related on the effect of heat losses on thermal stratification has been done [19–21]. Cruickshank and Harrison [19] performed experimental and simulated studies on the heat loss characteristics for typical solar domestic hot water storages. Their results found that U values in different nodes of a stratified tank obtained from both simulation and experiment were in relatively good agreement. Their work, however, only covered a small temperature gradient in the storage tank. Haller et al. [20] proposed a method to determine the stratification efficiency independently from heat losses. The application of the new method to experimental results showed that small deviations in the energy balance that are caused by measurement uncertainties had a large effect on the stratification efficiency based on an entropy balance. A numerical and experimental study on flow in a hot water tank due to standby heat loss was carried out by Fan and Furbo [21]. Their results showed that CFD calculations predicted satisfactorily the water temperatures at different levels of the tank during cooling of the tank. It was also shown that without the presence of strong thermal stratification there was buoyancy driven downward flow along the tank side walls due to heat loss of the tank and a corresponding upward flow in the center part of the tank.

From the literature review, it is evident that very few papers have evaluated the effect of heat losses to the surroundings on thermal stratification for thermal oil storage tanks which operate above the normal boiling point of water. In attempt to evaluate thermal stratification in an oil storage tank subjected to heat losses, an experimental setup to measure the thermal gradient in an un-insulated oil storage tank is presented. An experimentally validated one-dimensional model for a parametric study on the effect of heat loss on thermal stratification is also presented.

2. Experimental setup and procedure

The main components of the experimental setup and the principle of operation of the setup are shown by the schematic diagram of Fig. 1. An oval gear pump (**3**) [22] controlled by a variable DC