Journal of Advanced Research in Mechanical Engineering and Technology
Volume 5, Issue 1&2 - 2018, Pg. No. 17-24
Peer Reviewed Journal
Research Article

Comparison of Experimental and Simulation Studies on Thermal Stratification in a Thermal Energy Storage System

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DOI: https://doi.org/10.24321/2454.8650.201802

Abstract

Renewable energy supplies are steadily gaining increasing importance in all the countries. In particular, solar energy being non-polluting, clean and inexhaustible has received wide attention among scientists and engineers. Though there are many advantages, an important factor is that solar energy is time dependent energy source with an intermittent character. Hence some form of thermal energy storage is necessary for the most effective utilization of this energy source. Most of the thermal energy storage systems in use rely on the specific heat or sensible heat of the storage material, such as water, oil and rock beds and they are known as sensible heat storage systems.

Thermal performance of sensible heat storage systems mainly depends on the thermal stratification. Thermal stratification in solar tanks is essential for a better performance of energy systems where these tanks are integrated.

The objective of this paper is to study the thermal stratification of energy storage tanks, by means of experiments and computer simulations. The current study is proposed in order to quantify the thermal stratification inside the storage. A special attention is given to the validation of the model considered in this study by using a commercial CFD tool ANSYS WORKBENCH-CFX. Good thermal stratification is vital in order to achieve high thermal performance on solar thermal storages where the tank design is one of the most important elements to accomplish it. As it is known, the best tank design depends on several factors such as the system typology and storage size. In this paper an attempt is made to quantify thermal stratification by considering two such influencing parameters with the help of experiments and computer simulations. With this work, it is possible to conclude what are the important design parameters to build up and best preserve thermal stratification in a solar energy storage tank.

Keywords: Thermal energy storage, Sensible heat storage, Thermal stratification, CFD, ANSYS-CFX, Influencing factors, Tank design

Introduction

Thermal stratified storage tanks are an effective management technique to improve the efficiency of solar thermal systems. Thermal stratification improves the overall performance of the systems by increasing the efficiency of solar collectors and by enhancing the temperature level of the water supplied to load. The modeling of thermal stratification in storage tanks is an important issue for the design and optimization of storage tanks in solar thermal systems. Since thermal stratification involves complex phenomena of heat transfer and fluid dynamics, the

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How to cite this article: Rao GN, Reddy KH. Comparison of Experimental and Simulation Studies on Thermal Stratification in a Thermal Energy Storage System. *J Adv Res Mech Engi Tech* 2018; 5(1&2): 17-24.

detailed modeling of storage tanks is a hard task.

The purpose of this work is to present a method of modeling thermal stratification, a brief description of thermal stratification phenomena and its influencing factors for a solar domestic water heater with a mantle heat exchanger as shown in fig1.

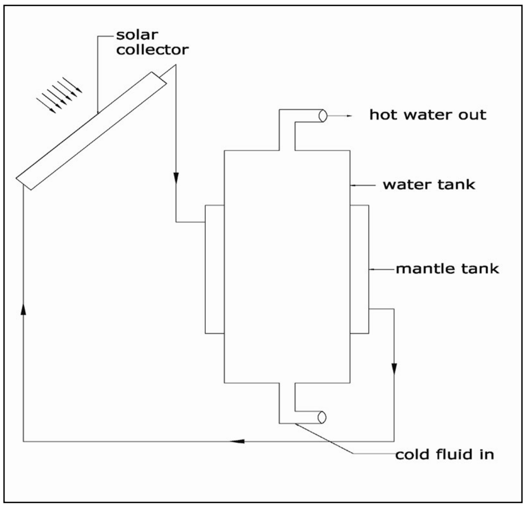

Figure 1.Solar water heater with mantle heat exchanger

Literature Review

Zurigat (1989), Shyu, (1990) investigated the factors influencing the thermal stratification degradation in solar energy tanks are forced convection flow through the tank, heat loss to the surrounding environment, thermal mixing at inlet, natural convection flow induced by conduction within the tank walls and heat diffusion inside the tank due to the vertical temperature gradient within the tank.

Lavan and Thompson (1977) performed an experimental study on a thermally stratified, vertical hot water storage tank. Experimental measurements were made on various height/diameter ratios, inlet port location and geometry, inlet-outlet temperature difference and different mass-flow rate. Their study showed that better thermal stratification can be obtained by increasing the ratio of the tank height to its diameter, increasing the diameter of the inlet port, or increasing the difference between the inlet and outlet water temperature

Cole and Bellinger (1982) concluded that maximum thermal stratification could be achieved inside the storage tank with a height to diameter ratio of four. The studies of Ismail et al. (1997) and Hahne and Chen (1998) confirmed Cole and Bllinger's conclusion while Nelson et al. (2000) suggested aspect ratio of three for the best thermal stratification.

Lightstone et al. (2000) showed that in the dynamic mode, the effect of wall thermal conductance on the thermal stratification degradation is negligible. Mixing flow in the inlet opening is considered one of the most important parameters in the degradation of thermal stratification. Therefore, in order to reduce the inlet mixing, different inlet configurations were considered and studied.

G. Naga Malleswara Rao and K. Hema Chandra Reddy (2011) performed many experiments on thermal energy storage system with mantle heat exchanger and studied the effect of various operating parameters on thermal stratification. In extension to their work, in this paper two such operating parameters have been studied and discussed.

Influencing Factors Of Thermal Stratification In Thermal Storage Tanks

As it is known cold water is heavier than warmer water which ascends to a layer with the same density. This is the natural process behind thermal stratification, a critical factor on the design of effective water heating systems with high thermal performances. In a well stratified storage tank high temperatures in the top and low temperatures in the bottom lead to better operation conditions of the solar system. Good stratification guarantees that the warmer water remains on the top of tank producing less starts and stops in the auxiliary energy mechanism. Further, the inlet water to the solar collector is removed from the lower and coldest part of the storage tank improving the operation conditions of the collector. Thus, the solar collector can be in use for longer periods without the use of auxiliary energy supply.

In order to achieve good stratification, several factors should be taken into account such as:

- Operating flow rates.
- Heat losses form the tank.
- Thermal conductivity of tank material
- Water mixing from inlet and draw-offs.
- Heat transfers from and to different tank levels for discharging and charging phase.

ISSN: 2454-8650
DOI: https://doi.org/10.24321/2454.8650.201802

- Thermal bridges especially in the upper part of the tank.
- Use of inlet stratifiers.

In order to accomplish a high efficient system several optimizations steps are needed. In this paper, five such parameters which influence the stratification in the solar tanks are investigated experimentally and the same are simulated by using CFD commercial tool ANSYS-CFX.

Evaluation of Thermal Stratification

The thermal stratification can be measured by the vertical temperature profile in the tank. A mixing layer is defined as the zone between hot and cold regions in the tank. This layer can be described by the share with a temperature range in respect to minimum and maximum temperature such as $T_{min} + 10\% (T_{max} - T_{min}) < T < T_{min} + 90\% (T_{max} - T_{min})$. The degree of stratification can also be expressed in terms of dimensionless temperature ratio which assumes a value between zero and one (0<θ<1) where θ is the degree of stratification and is calculated mathematically by the following equation. (Robert Huhn, 2006)

$$\theta = \frac{T - T_{min}}{T_{max} - T_{min}} \quad \text{---------- (1)}$$

Where T is temperature of mixing layer in the tank
T_{min} is cold fluid inlet temperature
T_{max} is mantle fluid inlet temperature
θ is the degree of stratification

Laboratory Experiments

A vertical mantle type heat exchanger with the dimensions as shown in figure 2 is fabricated for the purpose of experimentation. The experimental set up is shown in figures 2&3. The mantle tank data is given in table 1.

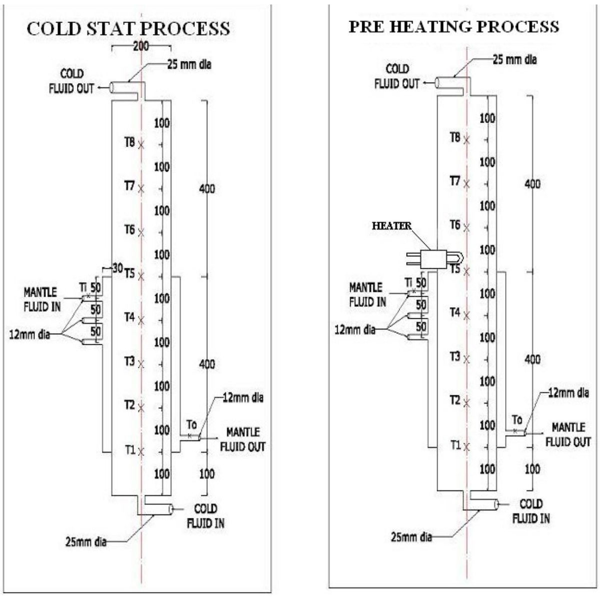

Figure 2.Solar water tank with mantle Heat exchanger

Figure 3.Photographic view of Experimental set up

ISSN: 2454-8650
DOI: https://doi.org/10.24321/2454.8650.201802

Table 1.Mantle Tank Details

Data of Mantle Tank		Stainless Steel Properties: Grade: SS 304	
Volume in inner tank [m^3]	0.0276	Specific heat [J/Kg.K]	460
Volume in inner tank above mantle [m^3]	0.01227	Density[Kg/m^3]	7820
Tank height [m]	0.900	Thermal Conductivity[W/ m^2.K]	15
Inner diameter of tank [m]	0.1976	INSULATION	
Thickness of tank wall [m]	0.0012		
Mantle height [m]	0.400	Material	Glass Wool
Mantle tank diameter[m]	0.260	Insulation top, [m]	0.010
Mantle top (distance from bottom of tank) [m]	0.500	Insulation side above/ below mantle, [m]	0.010
Mantle bottom(distance from bottom of tank [m]	0.100	Insulation side mantle,[m]	0.010
Mantle gap width [m]	0.030		
Mantle inlet position from top of mantle[m]	0.05 / 0.10/ 0.15	Insulation bottom, [m]	0.010
Mantle inlet size [inner diameter] [m]	0.012		
Hot water tank volume[m^3]	0.073		
Inner tank inlet size[m]	0.0254	Mantle Fluid	Water

The physical shape of the energy storage tank under consideration in this work is a vertical cylinder with mantle heat exchanger acting as a hot water jacket which surrounds part of the tank lateral surface. The mantle is constructed with an annular spacing of 30mm wrapped around the bottom half of a stainless steel (SS304 Grade) tank as shown in fig 2. The tank is insulated with glass wool. The experiments are carried out at Heat Transfer Laboratory of JNT University, Anantapur of Andhra Pradesh, India. (GNMRAO, 2013)

In the experiments, hot water is injected to the hot side of the heat exchanger from a conventional hot water tank acting as the heat source uniformly in the upper section of the heat exchanger and after heat exchange with the fluid inside the tank, it is withdrawn from the bottom part of the heat exchanger. The velocity of the inlet flow to the mantle heat exchanger is calculated according to the inlet hot water flow rate and the cross sectional area of the inlet of the heat exchanger. The diameter of the vertical thermal storage tank is equal to 0.222H and gap width in the mantle heat exchanger is 0.0333H., where H is the height of the storage tank.

A schematic diagram of the indoor experimental setup is illustrated in fig. 2&3 together with the instruments installed for the tests. Eight thermocouples made up of copper-constantan are fitted at different levels inside the core of the tank (fig. 2&3) and four thermocouples made up of copper-constantan are mounted on the mantle tank wall side of the heat exchange surface to measure tank temperatures at different locations and to know the stratification. The inlet & outlet temperatures and flow rate of the hot water (mantle fluid) through the heat exchanger are also measured. The thermocouples are used to measure the temperatures of selected locations in the tank. $3\frac{1}{2}$ digit digital display is used to display the temperatures.

CFD Modeling

The simulation is carried out on the computational domain as shown in figure 4. In this paper, a model of a solar domestic hot water tank with a vertical mantle heat exchanger has been incorporated in the commercial CFD software ANSYS-CFX (15.0) and the results are compared to the experimental results.

The experiments are first simulated by taking into account of the steady state natural convective flow on the tank side. A 3-D CFD model of a mantle heat exchanger coupled with a storage tank is developed with the same dimensions as the prototype unit. The computational domain is simplified by modeling the mantle tank system into three regions which made the problem simpler. High concentration mesh is used in the high temperature gradient regions near the heat transfer wall between the mantle and the storage tank. A total of 543324 grid points are used in the computational domain within the mantle gap and the inner tank. The number of grid points is given in table 2.

For each simulation, the inlet temperature, flow rate of mantle fluid and flow rate of cold fluid from the experiments are specified as inputs to the CFD model. The typical running time for simulation is approximately 3 days. On the tank side, the temperature profile along the tank height is initialized based on the measured data. Figures 4 and 5 show the geometry and mesh models of the work respectively.

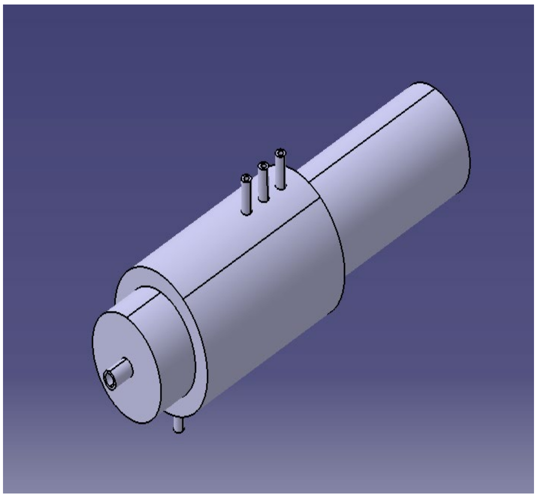

Figure 4

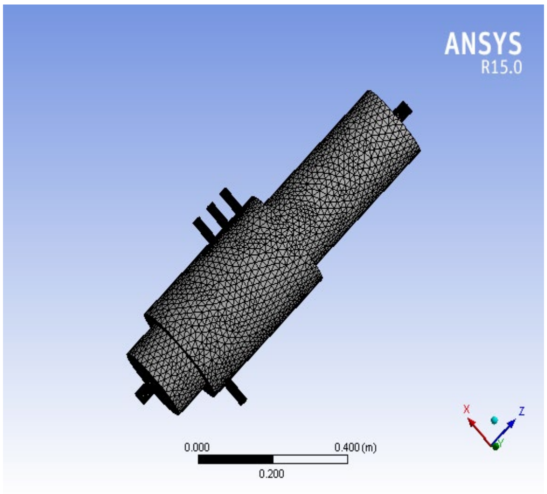

Figure 5

Figures 4 & 5.3-D modeling & mesh model of solar water tank with mantle heat exchanger

Table 2.Mesh Information

Domain	Nodes	Elements
Region1	44576	266563
Region2	495784	1297471
Region3	2964	10054

Validation of Models

In order to examine the validity of the CFD simulation models used for heat transfer studies in mantle heat exchangers, simulated results are compared to experimental data. Figure6 shows a comparison of tank temperature stratification between experiments and simulations of the cold start test with inlet temperatures of 50°C with a flow rate of 0.75lit/min (0.0125 kg/sec). As observed, the predicted tank temperature stratification is in reasonable agreement with the measured temperature profiles.

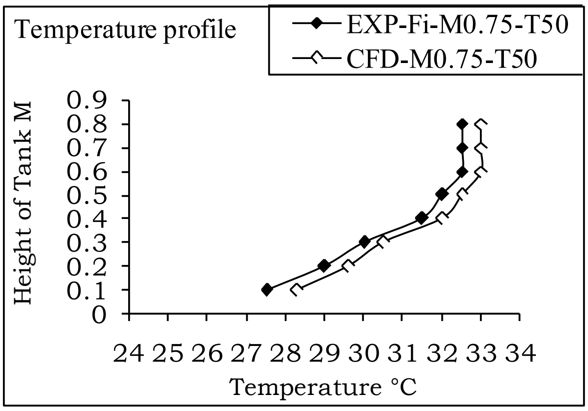

Figure 6.A comparison of tank temperatures between experiments and simulations

Results and Discussions

Investigating the process of formation of thermal stratification inside the storage tank for various governing parameters is the main objective of the present study. In this paper, the effect of following two parameters on thermal stratification in energy storage systems are considered in order to study and quantify the thermal stratification in energy storage tanks.

- Type of condition of start of experiment.
- Type of mantle fluid entry into the mantle heat exchanger.

5.1. Effect of startup methods of the experiment (Exp I-1-A, I-1-C, I-1-A- Pr, I-1-C-Pr)

The tests on the heat storages are carried out for two different initial conditions viz., Cold Start, the entire tank is maintained at around 26ºC or Pre-heated maintained at 80°C while the bottom portion is maintained at 26ºC. The second initial condition is created as discussed below. All the water in the inner tank is heated to 80ºC by an

ISSN: 2454-8650
DOI: https://doi.org/10.24321/2454.8650.201802

auxiliary heater located in the inner tank, and then approximately half of the volume of the inner tank is changed with cold water. The cold water is allowed to enter at the bottom with a flow rate of 1 l/min while the hot water leaves from the top at the same flow rate.

It is observed from the graphs 7 & 8, at high inlet temperature, degree of stratification is high in case of cold start condition comparatively with moderate inlet temperature. But the degree of stratification is high in case of pre-heat startup method at moderate inlet temperature because of well built thermocline region inside the tank which is slowly possible in cold startup method. This implies stratification profile is additionally dependent upon the initial stratification inside the tank.

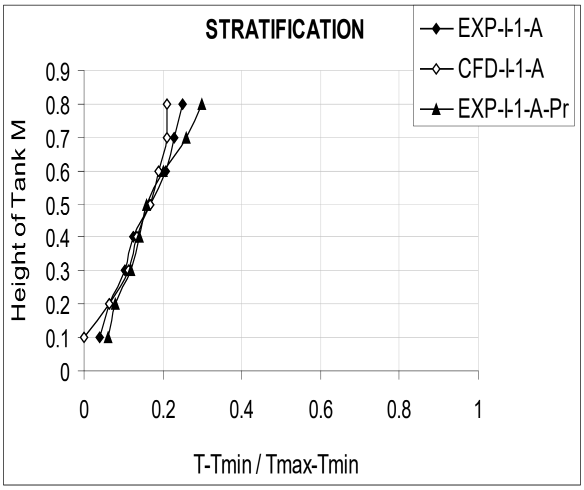

Figure 7

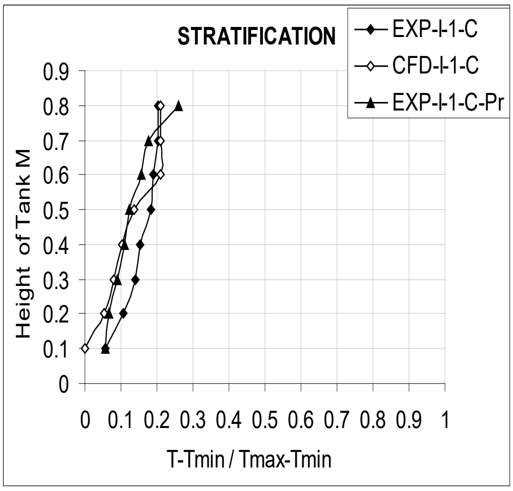

Figure 8

Figures 7 & 8.Thermal Stratification in experiments I-1-A, I-1-C, I-1-A- Pr, I-1-C-Pr

Effect of type of fluid entry (exp I-1-A, I-1-A-Spray, and I-1-A-Noz)

A possible technique to increase the thermal stratification by the mantle tank system is by injecting mantle fluid into the mantle. Experimentally it is proved that, both spray injection and nozzle injections of mantle fluid can enhance the thermal stratification even at early stages of the experiments. In spray and nozzle injection methods, the inlet design for mantle fluid is composed of a thin tin sheet of 2 mm thick with a narrow exit. For spray injection, small holes are made at the exit of tin sheet tube to sprinkle mantle fluid over the mantle inner wall, as shown in fig.9. The fig 10 shows a nozzle injection in which mantle fluid is allowed to flow through a nozzle of 6 mm diameter into the mantle tank.

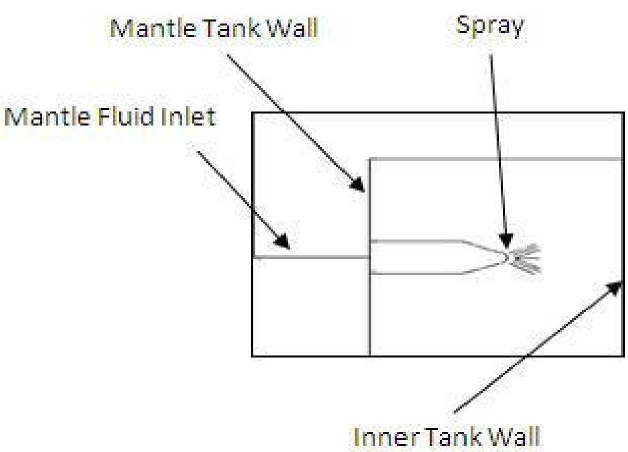

Figure 9.Spray injection into mantle tank

ISSN: 2454-8650
DOI: https://doi.org/10.24321/2454.8650.201802

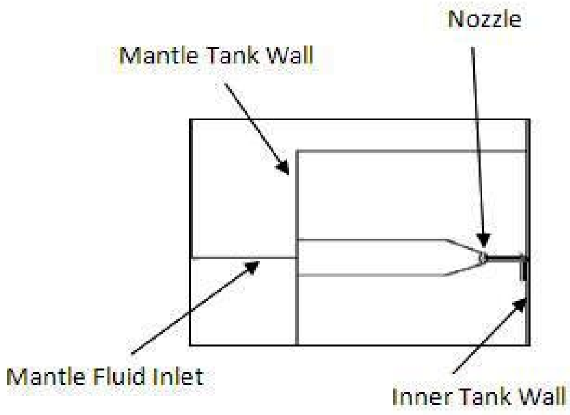

Figure 10.Nozzle injection into mantle tank

It is due to the more surface contact area between the hot fluid and mantle inner wall. The hot mantle fluid slides over the mantle inner wall for longer time due to the direct impingement of hot fluid than in regular injection which can thus improve the heat transfer. The figures 11 & 12 show clearly the high rates of stratification with spray and nozzle injections.

possible with high mass flow rates and direct impingement of mantle fluid. The specific properties of heat transfer fluids which have great impact on stratification are the coefficient of thermal expansion, viscosity & specific heat.

It is clearly evident from the above study that an initial stratification is necessary to attain high degree of

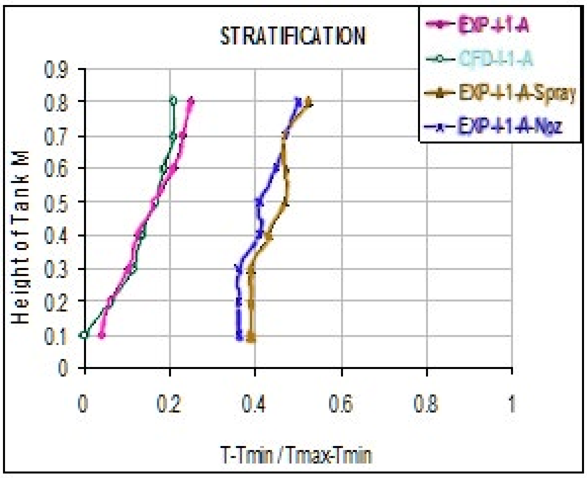

Figure 11

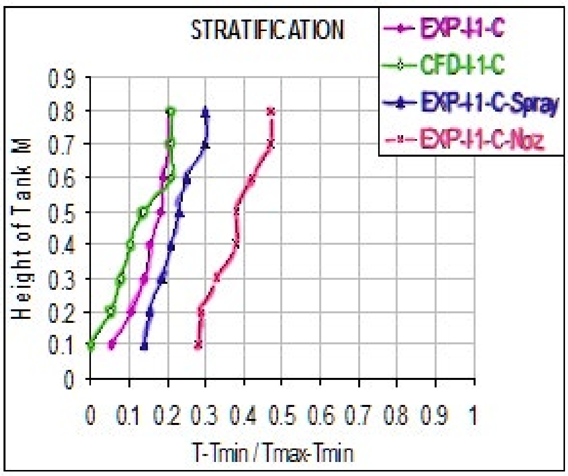

Figure 12

Figures 11 & 12.Thermal Stratification in experiments I-1-A, I-1-A-Spray, and I-1-A-Noz

Conclusions

The study of stratification is important for determining the weighted average temperature which is the sole parameter to evaluate the total heat gained by the water inside the tank. Through experiments and CFD analysis, it is ascertained that stratification inside the storage tank of solar domestic water heater with a mantle heat exchanger is influenced by several factors. These include mantle fluid inlet position, mass flow rates of mantle fluid, heat transfer fluids, startup methods and mantle fluid injection as well as initial degree of stratification of the water inside the tank.

The study of this work reveals that, there should be more contact between the hot mantle fluid and inner mantle wall to impart heat quickly to the tank contents. This is

stratification inside the tank which is possible with pre-heat startup method. It is also noticed that, the direct impingement of mantle fluid on to the inner mantle wall will enhance stratification but much care is to be taken to maintain the constant mass flow rate.

The investigations in this study showed that the CFD tool CFX-11.0 has the capability to predict buoyancy-driven heat flows. The simulation results are in good agreement with the experiments.

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Date of Submission: 2018-02-25
Date of Acceptance: 2018-03-30