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Thermal Stratification in Hot Fluid Storage - A Review

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Abstract—*Thermal stratification refers to formation of temperature layers within a hot storage tank. The phenomena occurs due to the change in density of the fluid with the temperature. Thermal stratification may be desirable in certain conditions such as solar hot water storage and the same may prove to be fatal in other conditions like storage of liquefied fuels. Thermal stratification depends on various factors. Vast amount of research is being carried out to find the dependence of stratification on various parameters and increase and decrease the degree of stratification as per the requirement. This paper presents an overview of different techniques developed and employed by various researchers to improve the stratification in solar hot water systems. The paper is mainly dominated by solar storage systems. Various numerical analysis techniques developed have also been discussed. Operation of storage tanks can be divided in two modes, viz. dynamic and static. This paper provides a brief discussion on both the modes and the effect of various design and operating parameters like inlet velocity, initial condition of tank, orientation of tank, shape of tank, aspect ratio etc. on the degree of stratification. This paper also provides an insight on the various CFD analysis carried out by the researchers. This review paper also deals with the suggestions of future scope of research that can be carried out in the direction of thermal stratification in solar hot water domestic system to increase the overall efficiency of the whole system.*

Keywords*: thermal stratification, solar hot water tanks, CFD analysis, thermal energy storage, static and dynamic mode.*

1. INTRODUCTION

Hot storage tanks are designed in order to store the fluids at higher temperatures and use it for when and where required. The requirement of thermal distribution inside the storage tank varies from one application to other. In case of solar applications, it is desirable to have cold water at the bottom and hot water at the top from where, water is supplied to the usage area. This phenomena of different temperature layers of fluid in fluid reservoirs is known as thermal stratification. As discussed, thermal stratification is desirable for solar applications s performance and efficiency of the whole system depends on it. [1][2]. The inflow of cold water to the solar collector is normally taken from bottom which is comparatively at lower temperature. Also the temperature of discharge water must be high to deliver required demand [1]. Main aim of solar hot water systems is to deliver hot water for longer duration of time [2]. This shows the importance of thermal stratification in case of solar systems.

For certain systems, thermal stratification may lead to danger. In case of storage of compressed gaseous fuels for example, the variation of temperature inside the tank may lead to heating in few some parts. Maximum temperature in a vehicle fuel system, according to standards and regulations is about 85^{o}[16]. Temperature higher than this can harm the material properties of the tank material. Sometimes, storage tanks are prone to thermal attacks. This may lead to a phenomena of BLEVE (boiling liquid expanding vapor explosion). The hazards of BLEVE are also dependent on thermal stratification [17]. In the applications like storage of fuel for flight vehicles stratification can be harmful. Due to stratification phenomena, liquid temperature will not be uniform which leads to accelerated pressurization; causing cavitation in pumps while pumping warm fluids at upper layers [12]. Study of thermal stratification thus becomes important to investigate the various parameters leading to thermal gradients and then finding ways to avoid it or at least decrease it for the purpose of safety.

In this paper authors have tried to establish an understanding of the factors leading to thermal stratification, factors leading to destratification, numerical methods developed and employed in order to investigate the same in various conditions and for doing so the parameters considered are design parameters like the inlet velocity, shape and size of the tank, use of various inserts inside the tank etc. and operating conditions both inside and outside like convection currents, heat flux and effect of insulation. Furthermore, on the basis of the presented study, the development of new techniques for solar storage systems are also presented.

2. LITERATURE REVIEW

Shahab Alizadeh [1] carried out an experimental and numerical analysis of thermal stratification in a horizontal cylinder solar storage tank. Author initially carried out four sets of experiment in which cold water was injected in the horizontal tank from the bottom side with three different thermal fields. The first set was with initial thermal stratification having inlet temperature same as that of the bottom temperature. In second set, inflow temperature was at relatively lower temperature than the bottom temperature. The tank was initially stratified in this as well. In third set, tank was initially isothermally heated. Forth set was same as that of first, the difference being that the straight inlet tube was replaced by a 30^o downward bent divergent conical tube. The results of the experiments showed that better stratification was obtained in the fourth set i.e. with the use of divergent tube due to the diffuser effect of the nozzle. A slightly improvement was noticed in the second set where bottom temperature was higher than injected water temperature. Two different types of one dimensional turbulent models, viz. Turbulent Mixing Model and Displacement Mixing Model was then developed by author to investigate the accuracy of experimental results. N. Altuntop et al. [2] numerically investigated the effect of water inlet velocity on thermal stratification in a mantled hot water storage tank. Aim of their study was to get high degree of thermal stratification and supply hot water for longer duration of time. In their study, they considered twelve different inlet velocities. Results revealed that the temperature of the tank increased with the increase in inlet velocities to the mantle but not in a proportional manner. Water circulation increased with the increase in velocity at the mantle inlet. Better thermal stratification was obtained. Water temperature increased with the increase in height inside the tank but for some of the models, increase rate was slightly low. With the increase in hot water inlet velocity to the mantle, heat transfer coefficient in the mantle increased but the increment was not linear. Authors suggest to implant longitudinal fins to solve this problem. Olfa Abdelhak [3] et al. performed a CFD analysis of thermal stratification in domestic hot water storage tank during dynamic mode. A three dimensional computational fluid dynamic model was built and analysis was performed using the commercial software fluent 6.3. Analysis was done for the charging and discharging mode to investigate the flow and heat transfer characteristics in the vertical hot water tank. The study was then extended to analyze the same for horizontal tank. Performance parameters like Discharge efficiency, Richardson and stratification numbers were used to evaluate the tanks. The study showed that in vertical tank, the amount of mixing is restricted near the inlet port while for the horizontal tank, two region of increased mixing was identified. Due to vortex formation in horizontal tank, draw off temperature and thus the discharging efficiency of the tank decreased. Richardson number and stratification efficiency of horizontal tank was found to lower than that of vertical tank. This clearly shows that vertical tank or vertical orientation is better than the horizontal and hence is generally preferred. Zheng Yang et al. [4] did a comparative study of the influences of different water tank shapes on thermal energy storage capacity and thermal stratification under static mode of operation and laminar natural convection. The study was experimental and numerical. New models were built for experimentation. Ten different shapes were studied numerically and experimentally. The results showed that the among all the shapes, sphere and water barrel tanks showed higher degree of thermal stratification and thus ate ideal for thermal energy storage. Based on the results, authors divided the shapes into three categories viz., shapes with sharpcorners, those with hemispheres, and those with horizontal plane surface. Sharp corners have higher stratification, while shapes with horizontal plane showed lowest. Shapes with hemispheres lied in between. Necdet Altuntop et al. [5] numerically looked at the effects of obstacles on thermal stratification in hot water storage tanks. Authors analyzed twelve different obstacles. Results showed that the placing obstacles inside the tank improves the thermal stratification of the tank. Among all, obstacles having gap in the center had better stratification as compared to the obstacles with side gaps. A. Álvarez et al. [6] also studied the thermo hydro-dynamic behaviour of the heat transfer fluid in a storage tank connected to a domestic solar collector. Experimental analysis was performed using three flat plate collectors connected to the storage tank. To closely investigate the thermal behaviour, a 3-D CFD analysis of whole assembly was carried out using COMSOL Multiphysics software. The study confirmed that thermal stratification decreases as the inlet/outlet distance to the top and bottom of the tank increases. Lana Kenjo et al. [7] also carried out experimental and numerical study of thermal stratification in a mantle tank of a solar domestic hot water system. For the effective analysis and optimization of the mantle tank of solar domestic hot water systems, long period of dynamic simulation is needed. Authors in their study, have proposed a new simpler numerical method to predict the thermal behaviour of within a tank heated by mantle exchanger. Initially, experimental tests were carried out to study the thermal behavior inside tank. On the basis of the results of the experimental results, numerical zonal model was developed to undertake long simulations. Numerical model mainly contained three parts. Heat transfer in the solid part as the mantle and the tank wall, heat transfer in the liquid part as the fluid in the mantle and in the tank and heat transfer between the solid and the fluid part. Model was developed in the TRNSYS computing environment. Zonal model is faster than the CFD model and can be used for long simulations of more than a year with a reasonable precision (<7%). Ashmore Mawire [8] did an experimental analysis and simulated thermal stratification evaluation of an uninsulated oil storage tank subjected to heat losses during charging. Authors aimed to evaluate the heat losses to the surrounding on the thermal stratification for thermal oil storage tanks operating above the normal boiling point of water. Experiment was performed to measure the thermal gradients in the tank. Numerical model was then developed to describe the thermal distribution using energy balance measure the heat loss to the surrounding. Thermal gradients were studied against time. It was found that thermal gradient rose to a maximum value at some time and then showed a down fall indicating thermal destratification in the tank due to heat loss to the surrounding. Parametric study showed that ambient temperature and lower value of heat loss factor plays a vital role in thermal stratification. Lower ambient temperature leads to better stratification. Jianyun Shi et al. [9] did an experimental research on thermal stratification of liquefied gas in tanks under thermal attack. Phenomenon of boiling liquid expanding vapor explosion (BLEVE) may occur when liquefied tank is exposed to fire. Effect of BLEVE is significantly dependent upon the thermal stratification of liquefied gas. In their study, authors have simulated the thermal response of liquefied gas tank under thermal attack. The results showed that there was no observable stratification and temperature was nearly uniform for the case wherein only liquid space wall was heated. Considerable stratification was seen when the liquid and vapor space were heated simultaneously. Abdul Jabbar N. Khalifa [10] et al. carried out experiments on temperature stratification in a thermal storage tank in the static mode for different ratios. Investigations were carried out during a stand-by mode on tanks with different aspect ratios. Tanks of aspect ratio 2, 1 and 1/2 were used for the study. Results showed that tanks with higher aspect ratios showed higher degree of stratification. For the tank with aspect ratio of 1/2, heat loss to the surrounding is more and so the top half of the tank becomes more stratified with time while the bottom region remains unchanged. For AR of 1, a small region at the top was weekly stratified but the lower region showed god degree of stratification. For AR of 2, stratification was clear. Heat loss to the surrounding is a measure factor in deterioration of thermal stratification. During cooling phase of stagnant operation, stratification decreased continuously. Mainak Bhaumik [11] did a CFD analysis of convective flow in solar domestic hot water storage tank. A 2-D model was build using ICEM and analysis was carried out in fluent. It was observed that thermal stratification was obtained for the lower inlet velocity i.e. for the laminar velocity. Due to lower velocity at inlet and outlet, there is no mixing in the tank and stratification is not degraded. Jing-Jie Ren et al. [12] did a simulation on thermal stratification and de-stratification in liquefied gas tanks. Model was developed n fluent 12.0 and was verified from the literature. Flow characteristics and thermal behaviour was studied during stratification and destratification. In a stratified liquid, semi circulation was observed near the liquid surface with flume like flow and a cold core rested under the surface which resisted the warmer circulating flow. As the cold core started disappearing, the resistance to warmer circulation decreased. Due to this circulation formed and de-stratification started. It continued until all of the stratified layer were destroyed from top to bottom. Marie Swiatek [13] worked on integrated collector storage solar water heater (ICSSWH) to enhance its stratification. The aim of the study was to increase the overall efficiency of the water heating system which can be done by increasing the thermal stratification in the tank attached to the heater. Experimental study was conducted upon a charge of high aspect ratio cavity (representing ICSSWH storage) in order to study stratification. Stratification was obtained using a stratification plate inserted in the middle of the tank. The study considered various angles (30^o, 45^o and 60^o w.r.t. horizontal), heat flux (1800, 2700 and 3600 W/m^2) and length of the stratification plate. Results showed that stratification increased with a higher value of heat flux and lower value angles. Degree of stratification was high for plates with shorter length. Study revealed different fluid zones with distinct behavior. Flow appeared to be 2-D except for the upper region for which 3-D flow pattern was observed. This was also the region where there was no stratification. When the position of the heated region was changed, the buoyancy force was seen to be decreased and when heated region was taken near the outlet, reversed flow was observed. Both bring about higher degree of stratification but here reversed flow was having more influence. The risk here was that of ending up with dead volume of heating zone wherein the fluid did not moved to bottom. María Gasque et al. [14] studied the influence of inner lining material on thermal stratification in a hot water storage tank. The analysis was done in a water tank during charging phase and after that on standby mode. Numerical analysis was carried out on a three dimensional Computational Fluid Dynamics (CFD) model which was validated from experimental model. Authors analyzed the temperature over time at severalheights, temperature profiles, velocity contours, water streamtraces and temperature contours, arestudied and compared for three different inner lining materials. Results showed that higher degree of thermal stratification was obtained for the lining material with lower thermal conductivity. The mixing due to wall conductance decreases and hence the stratification is maintained. With the help of this result, authors can conclude that applying a coat of insulating paint as inner lining for hot water storage tanks may result in higher stratification. Jinny Rhee et al. [15] experimentally did thermal stratification from thermal diodes in solar hot water storage tank. Authors used various modifications of a double chimney device which they called as a thermal diode. They were designed in such a manner as one chimney would only let movement of hot fluid from bottom to top while the other would transfer cold fluid from top to bottom during the standby operation of hot storage tank. The device were used with an aim to increase the degree of thermal stratification inside the tank. Experiments were performed with different models. The results showed an increment in the stratification levels. The modification named 'express elevator' starting from the lower $1/3^{rd}$ and leading hot fluid to the upper $1/3^{rd}$ region of the tank showed highest degree of stratification. It showed three times enhancement as compared to the tank without diodes. Igor Simonovski et al. [16] performed thermal simulations of a hydrogen storage tank during fast filling. In order to determine the temperature distribution of hydrogen storage tank, authors performed a FEA analysis on heat transfer process across tank walls. Analysis was based upon the thermal parameters like tank wall thermalconductivity, specific heat capacity, density and heat transfer coefficient between thetank's external surface and the ambient air. Results showed that the properties of the tank's composite have a profound effect on the temperature distribution as compared to the plastic liner. During filling process, heat transfer coefficient between the tank wall and ambient had very less or no effect on thermal behaviour, but played a significant role during the standby mode. Also, increasing the liner thickness of plastic, resulted in decrease in the composite layer's temperature. Jianhua Fan [17] did a numerical simulation of thermal stratification in a vertical cylinder hot water tank in operating in standby mode and losing heat to the surrounding. Authors initially calculated the heat transfer coefficient by transient fluid flow and heat transfer during the standby mode using CFD. This value of heat transfer coefficient obtained at different parts of the tank was used as an input in the validated CFD model to analyze the influence of upward and downward flows on the thermal stratification in the central parts of the tank. Investigations were based on the tank parameters like tank volume, height to diameter ratio and insulation and different initial conditions of the tank. It was found that the thermal stratification depends on the natural convection and also, heat loss from the sides gets distributed at different levels of the tank at various thermal conditions. To characterize the buoyancy driven flow on exchange of heat loss between tank layers by natural convection, authors introduced a heat loss removal factor and based on the results obtained, a generalized equation for the heat loss removal factor was formulated taking into account the tank parameters. The equation was validated for the current model and can be used for optimization and design programs of the same. Ulrike Jordan [18] worked on a thermal stratification in small solar domestic storage tanks caused by draw-offs. In their study, authors compared different cold water inlet devices for SDHW systems. The objective was to investigate the effect of cold water inlet devices on thermal stratification in marketed tanks and to find enhancement for performance. Two inlet designs, one connected to small curved plate and the other to a larger plate are compared. Water enters from the bottom in the vertical direction. An expanded multi-node storage model was used for the simulation. Inlet device with a large plate led to increase in solar fraction of about 1-3% points in annual system simulations. Wahiba Yaïci et al. [19] carried out a three dimensional unsteady CFD simulations of a thermal storage tank performance for optimum design to investigate the effect of various designs and operating parameters during charging operation on the flow characteristics , temperature distribution and performance of hot water storage tank. Various design and parameter cases were studied computationally. Their work confirmed previous observations and also showed how an appropriately design tank can lead to better thermal stratification. Authors concluded that 3D transient CFD simulation is an effective tool for optimizing thermal storage parameters at an early stage which may lead to improved and efficient performance of a tank thus increasing the overall efficiency of the solar thermal systems.

3. FUTURE SCOPE

In solar applications, thermal stratification is a much desirable phenomena. To obtain it, the most important factor is avoiding mixing of the two fluid regimes. Many studies have shown to use inserts in order to avoid mixing and improve stratification. Other factor is the turbulence. Vertical tanks are best suited for stratification but in domestic applications, horizontal tank is preferred due to elegance. Enhancement of the horizontal tank can be undertaken as a study in order to improve the thermal stratification. This would be helpful in increasing the overall efficiency of the system. To reduce the mixing rate, insulating baffles may be used. Also a comparison between a tank of metallic material and conducting material in horizontal orientation may be done in order to investigate the thermal behavior of the fluid. Inserts for dynamic and static mode may be chosen to increase the stratification. Another idea is use perforated baffles inside the tank. In order to avoid stratification in tanks where it is not desirable, internal stirring and heating can be considered as a way to degrade stratification or avoid it.

REFERENCES

[1] Shahab Alizadeh; An Experimental And Numerical Study Of ThermalStratification In A Horizontal Cylindrical Solar StorageTank;Solar EnergyVol. 66, No. 6, pp. 409–421, 1999.

[2] N. Altuntop, Z. Kilik, V. Ozceyhan and O. Kincay; Effect of water inlet velocity on thermal stratification in amantled hot water storage tank;International Journal Of Energy ResearchInt. J. Energy Res. 2006; 30:163–176.

[3] Olfa Abdelhak, Hatem Mhiri, Philippe Bournot; CFD analysis of thermal stratification in domestic hot water storagetank during dynamic mode;BUILD SIMUL (2015) 8: 421–429.

[4] Zheng Yang, Haisheng Chen*, Liang Wang, Yong Sheng, Yifei Wang;Comparative study of the influences of different water tank shapes onthermal energy storage capacity and thermal stratification; Renewable Energy 85 (2016) 31-44.

[5] Necdet Altuntop, Mevlut Arslan, Veysel Ozceyhan, Mehmet Kanoglu;Effect of obstacles on thermal stratificationin hot water storage tanks; Applied Thermal Engineering 25 (2005) 2285–2298.

[6] A. Álvarez, M. Baz, O. Cabeza, J.L. Ferrín, M.C. Muñiz and L.M. Varela; Experimental and numerical simulation of a storage tank connected to a flat-platesolar collector; International Conference on Renewable Energies and Power Quality (ICREPQ'13)Bilbao (Spain), 20th to 22th March, 2013.

[7] Lana Kenjo, Christian Inard, Dominique Caccavelli;Experimental and numerical study of thermal stratificationin a mantle tank of a solar domestic hot water system; Applied Thermal Engineering 27 (2007) 1986–1995.

[8] Ashmore Mawire; Experimental and simulated thermal stratification evaluation of an oilstorage tank subjected to heat losses during charging; Applied Energy 108 (2013) 459–465.

[9] Jianyun Shi, Mingshu Bi, Xue Yang; Experimental research on thermal stratification of liquefied gas in tanks underexternal thermal attack; Experimental Thermal and Fluid Science 41 (2012) 77–83.

[10] Abdul Jabbar N. Khalifa, Ayad T. Mustafa and Farhan A. Khammas; Experimental study of temperature stratification ina

thermal storage tank in the static mode fordifferent aspect ratios; ARPN Journal of Engineering and Applied Sciences vol. 6, no. 2, February 2011, 53- 60.
[11] Mainak Bhaumik;CFD analysis of convective flow in a solar domestic hot water storage tank; International Journal of Scientific & Engineering Research Volume 4, Issue 1, January-2013, 1-6.
[12] Jing-Jie Ren, Jian-Yun Shi, Peng Liu, Ming-Shu Bi, Kai Jia; Simulation on thermal stratification and de-stratification inliquefied gas tanks; international journal of hydrogen energy 38 (2013) 4017-4023.
[13] Marie Swiatek, Gilles Fraisse, Mickael Pailha; Stratification enhancement for an integrated collector storage solarwater heater (ICSSWH); Energy and Buildings 106 (2015) 35–43.
[14] María Gasque, Pablo Gonzalez-Altozano, Daniel Maurer, Ignacio Jose Moncho-Esteve, Rosa Penelope Gutierrez-Colomer, Guillermo Palau-Salvador, Eugenio García-Marí; Study of the influence of inner lining material on thermal stratificationin a hot water storage tank; Applied Thermal Engineering 75 (2015) 344-356.
[15] Jinny Rhee, Andrew Campbell, Adele Mariadass, Branden Morhous; Temperature stratification from thermal diodes in solar hotwater storage tank; Solar Energy 84 (2010) 507–511.
[16] Igor Simonovski, Daniele Baraldi*, Daniele Melideo, Beatriz Acosta-Iborra; Thermal simulations of a hydrogen storage tankduring fast filling; international journal of hydrogen energy 40 (2015) 12560-12571.
[17] Jianhua Fan, Simon Furbo;Thermal stratification in a hot water tank established by heat lossfrom the tank; Solar Energy 86 (2012) 3460–3469.
[18] Ulrike Jordan, Simon Furbo; Thermal stratification in small solar domestic storage tankscaused by draw-offs; Solar Energy 78 (2005) 291–300.
[19] Wahiba Yaïci, Mohamed Ghorab, Evgueniy Entchev, Skip Hayden; Three-dimensional unsteady CFD simulations of a thermal storagetank performance for optimum design; Applied Thermal Engineering 60 (2013) 152-163.