International Journal of Research in Science and Technology
Volume 9, Issue 2: April - June, 2022
ISSN 2394 - 9554

TRANSIENT THREE-DIMENSIONAL COMPUTATIONAL ANALYSIS OF THERMAL STRATIFICATION TANK

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ABSTRACT
The recovery of heat energy from the process industries become significant due to the energy crises and global norms. The dying and dairy industries are rejecting significant amount of heat to the surroundings without being utilized. The common practice is that the waste heat is recovered from the drain by the application of heat exchangers, and this energy is stored for a short period at thermal stratification tank. This tank has a configuration such that, the hot water is allowed to reside at upside, while the low temperature water is being attendant on the below side. The factors that affects the stratification for thermal process in the tank is found to be the length to diameter ratio of this tank and mass flow rate of the caring fluid, the positioning effect of the inlet section and the outlet section. The research work aims to compute the effect on transient, three-dimensional, thermal stratification process with due concern to the factors in charge.

Keywords: Stratification effect, Buoyancy, Momentum diffusion.

INTRODUCTION
Thermal stratification has a significant impact on the energy efficiency of many systems with a thermal storage tank. In the perspective of dying industries, there are many stages carried out to process the cloths such as pre-heating, scouring and hot-wash. These processes require thermal energy as a prime input, which is supplied in the form of steam. At the end of these stages, liquor (dye+water) at high temperatures is formed. Pumping this liquor to the heat exchanger where it exchanges the temperature with the low temperature fluid present at the bottom side of this stratification tank. High temperature fluid from the heat exchanger is used to increase the temperature of the air in stratification tank. The challenge here is to charge the hot fluid with minimal mixing with the low temperature water in the stratification tank because if the cold and hot fluid is mixed, they will reach a temperature that is less than the temperature of charging hot fluid. Additionally, it aims to keep the mixed temperature constant throughout the stratification tank. Maintaining the temperature stratification in the storage tank improves the effectiveness of the entire thermal system. The degree of thermal stratification produced inside the tank determines how energy-efficient the system with the hot water storage tank . Several factors, including the tank's length to diameter ratio, charging mass flow rate, and the locations of the inlet and outlet, have an impact on thermal stratification. The other important parameter which affects the mixing effect is buoyancy. As hot water is more buoyant with cold water, this low temperature fluid is allowed to sent through the lower side of the tank to maintain the thermal stratification. The thermocline is the region between the high and low temperature fluids and it is indicator for thermal stratification. If the thermocline thickness is too high, then the thermal stratification is less.

F. J. Oppel et al [1] created a 2D finite difference model for anticipating the temperature inside of thermal stratification tank. These results compared with the physical test results. Anguli Li et al[2] performed computational fluid dynamic analysis on the affect of tank structures on the stratification process for solar hot water systems. The authors performed the experiment on a cylindrical tank, truncated cylindrical structure and found out that at the diameter ratio of 0.554 for the cylindrical tank, good results of stratification was achieved. Bouhal et al [3] performed the three-dimensional computational analysis on the effect of baffles at the various positions on thermal stratification interior side of tank. Authors proved the superior process of stratification achieved by placing the baffle which was positioned at the middle of the tank. Zacher et al [4] carried out the test study on the impact of the baffle at the inlet channel in stratification tank. Experimental results were validated against the simulated results by them. Buruk Krusan et al [5] did a computational investigation on the influences of different types of insulation geometry on the stratification inside the tank. They concluded that the truncated and pyramid-shaped insulated model for hollow and the block-shaped tank model has improved the thermal stratification. Buruk Krusan et al [6] further performed a computational study on the impact of the section of a block shaped tank on stratification inside the tank and they found out that providing inclination to the rectangular tank improves stratification. Jose Monacho et al [7] expressed a numerical investigation on effect of varies types of invent devices such as diffusers on stratification inside the tank. Maria Gasque et al [8-17] performed the computational analysis on impact of interior fabric material on stratification tank. Janne

Dragstad et.al [9-15] performed the experimental study about the effect of various types of inlet channels inside the tank. The author stated that stratifies from technology of EyeCular ApS had a distant better action at flow volume of 1-2 litre per minute and the stratified form Solvis GmbH and other Co KG had a good action at 4 litre per minute. Shu-hong et.al [10-16] performed the experimental study of varies invent devices on thermal stratification at the inside tank. They found that slot kind of inlet has increased in thermal stratification inside the tank compared with other conventional inlet devices. Dogan Ermedir and Necdet Altuntop [11] performed an test investigation on the inflation of thermal stratification on the high temperature fluid storage tank by locating different four obstacles at four different positions inside the hot water tank. They established that stratification tank was enhanced by placing the obstacles at a lenght of 200mm from the above side and bottom of tank. Brown and Lai [12] performed the test investigation on influences of thermal stratification tank in the hot water fluid accumulating tank for solar application using 15porous inlet manifold and proved that porous manifold reduces high temperature and low temperature fluid mixing and able with maintain a stable thermal stratification. Zheng Yang et.al [13] showedthe physical test study of impact on different shapes of hot water storage tanks on stratification. Among ten various shapes studied, the cylinder and the barrel-shaped hot water storage tanks were found suitable for hot water storage applications. A. Castell et.al [14] did trail test analysis find out most useful dimensionless number to characterize the thermal stratification. Richardson's no. is the best number about characterizing stratification and the mixed no. has some problems [20-21]. There are many attempts to model the thermal stratification interior side and many are pertaining to two-dimensional models. The two-dimensional models have the limitations to predict the temperature distribution of the three-dimensional tanks with accuracy. It is require developing a three-dimensional computational model to predict the heat distribution inner side the stratification tank and this model should analyze the effect of various parameters on stratification. This work illustrates 3-dimensional transient computational modeling to identify the heat distribution of tank at inner side and effect of various parameters on the thermal stratification is analyzed and is presented.

GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

Governing Equations

Flow field for the system is governed by energy, continuity and momentum equations and by solving simultaneously using the finite difference method or finite-volume method the flow parameters can be predicted. The appropriate boundary conditions to be specified to obtain the solution specific to the system under study. Analogously, the temperature of the system can be found by solving the energy equation with boundary conditions of the specific system under study. This study considers the Navier-Stokes equation as the momentum equation since the working fluid is water, which is a real fluid and has viscosity. The momentum conservation equation in a differential form including the buoyancy forces is written as below

$$\rho\frac{\partial u}{\partial t} + (\rho u.\nabla)u = -\nabla p + \nabla.\tau - \rho\beta(T - T_{ref})g \qquad (1)$$

Similarly, the energy equation in differential form is written as

$$\rho Cp\frac{\partial T}{\partial t} + (\rho Cp\, u.\nabla T) = \nabla.(k\nabla T) \qquad (2)$$

Boundary Condition

An initial temperature of the storage tank is kept at 303K. Inlet boundary conditions are initialized for each case discussed in this work as velocity and the normal pressure outlet boundary conditions are set for the outlet with the outlet weight-age ratio of 1.0. Adiabatic boundary conditions are applied for the walls, which means the heat transfer to the surroundings is zero. This is a valid boundary condition because the thermal storage tank is usually insulated. No-slip conditions give at the walls, which mean the velocity of the water in immediate contact with the wall is zero. The variation of density of water with temperature is given into the solver as discrete values and they interpolated linearly for intermediate values. The governing equation of mass, momentum, energy is work out by using the FVM technique.

Model Geometry and Meshing

The tank is modelled using CREO software and the IGS file of the geometry is imported to the ANSYS Workbench for further analysis. Figure 1 illustrates the geometry of the tank. It comprises of one invent port and one out port. The high temperature water is passing through the inlet port positioned at top & the low temperature fluid is removed at below the tank through outport. The dimensions of both inlet & outlet ports are kept constant for all the simulations. The dimensions of the tank, the position of the inlet and the outlet ports and mass flow rate of hot water are parameterized.

 ISSN 2394 - 9554

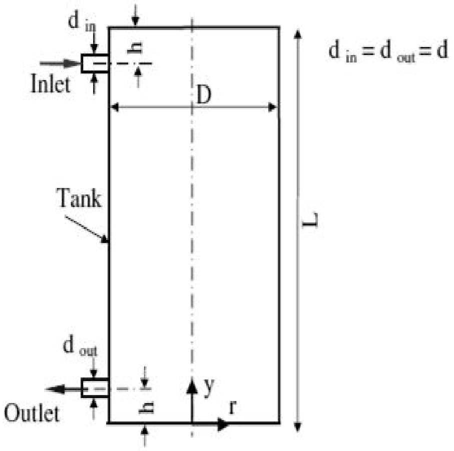
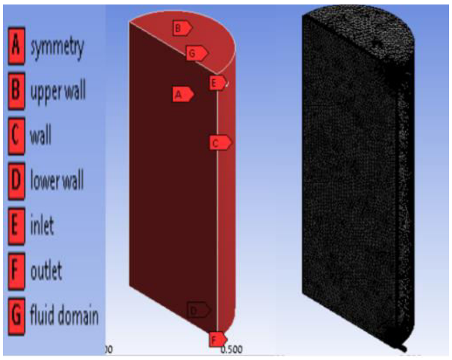


Figure 1. Geometry of the tank

Geometry being cylindrical, an unstructured mesh is created using ICEM Meshing software. The meshed geometry of the domain shown in Figure 2. In arrange to spare computational duration, one-half part cylinder is modelled and meshed. The symmetry boundary conditions are enabled systematically. The number of elements varies between 2,39,748 and 3,15,526 depending on the case. The fine mesh is done around the areas of the inlet and the outlet, where the flow parameter changes are expected to be high. The inflation cells are added to the boundary of the symmetry wall to capture the viscous phenomena near the wall.



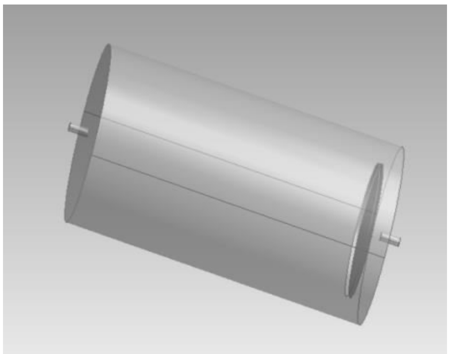
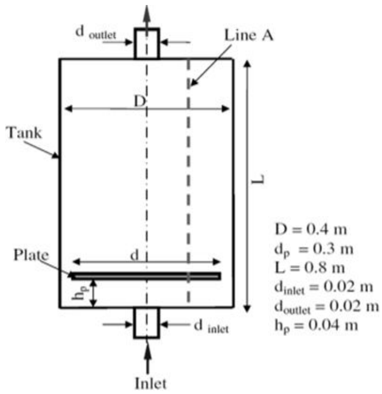


Figure 2. Meshed view of geometry **Figure 3.** Geometry developed for validation

Zacher in 2003[4] experimented with charging cold water at 20°C into the thermal storage tank that which contains the hot water at 41°C. The length and diameter of the tank are 0.8 and 0.4 m respectively. The geometry is modelled in Figure 3 for this computational study based on the author's quoted literature. Figure 4 describes the geometry of the stratification tank.Zacher [4] noted that the temperature of the tank along the line-A at the transverse mid-plane of the tank, which was offset by 100 mm from the centre-line of the tank, using an array of 20 thermocouples. The results of his experiment are shown in Figure 5.



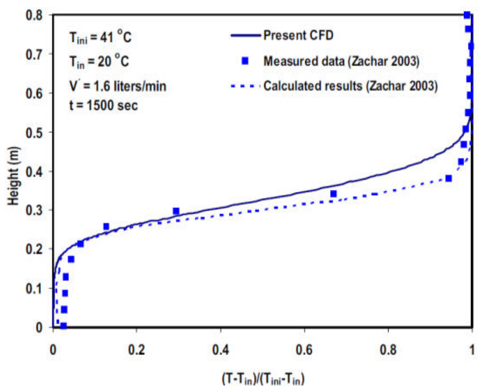


Figure 4. Geometry of the stratification tank **Figure 5.** Temperature along with the height of storage tank

In his experiment, Cold water is poured into the tank from the bottom once the tank has been filled with hot water. The same scenario is simulated with the corresponding boundary conditions. The temperature contour at the mid-plane is obtained at 1500 seconds [25 minutes, preferably saturates, and attains steadiness in flow field variable fluctuations] which is plotted in Figure 6.

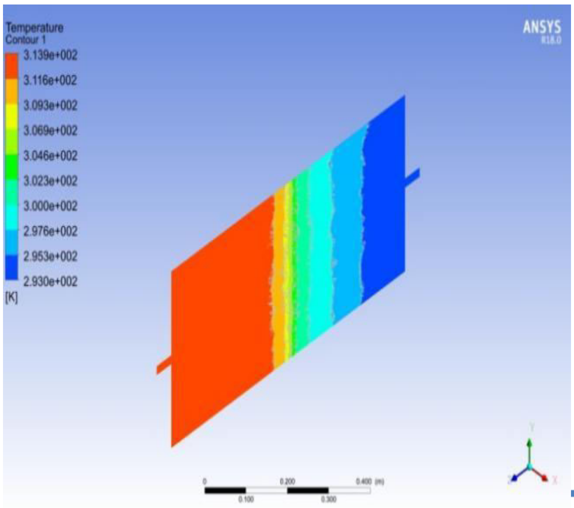


Figure 6. Temperature Contour at Mid-plane of Storage Tank by the end of 1500 seconds

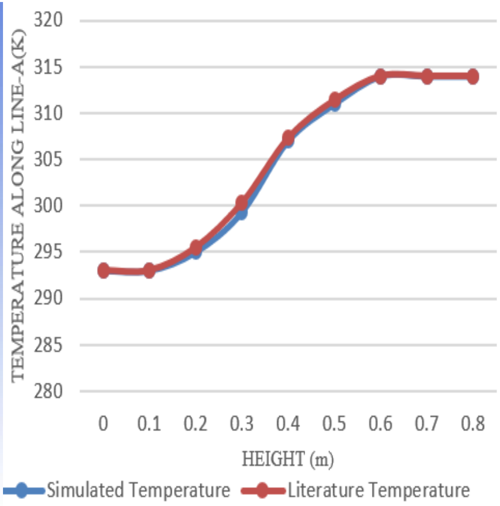


Figure 7. Comparison of temperature in the simulated and experimental case [Zacher]

The temperature along line-A is noted and is validated against the experimental result which is shown in Figure 7. The findings demonstrate that the model accurately predicts the temperature within the hot water storage tank; the largest difference between the simulated and experimental temperatures is 1°C. The simulated temperature and the findings reported in the literature correspond well. In order to investigate the impacts of different influencing characteristics on thermal stratification of stratified storage tanks, the model is used to predict the temperature of hot water stratified thermal storage tanks.

Effects of L/D Ratio of Tank on Thermal Stratification

Two instances are used to examine how the L/D ratio affects thermal stratification. In the first scenario, the tank's diameter is varied but its length is kept fixed. In the second scenario, the tank's diameter is maintained while its length is specified. When the tank's diameter is decreased, the L/D ratio rises and the tank's volume falls. In addition to increasing the tank's volume, lengthening the tank increases its L/D ratio.

Variation of Tank Diameter by Holding the Length as Constant

The details of the simulation are shown in Table1. In this study, the tank with different aspect ratios (AR) such as 3.0, 2.5, 2.0 is simulated.

Table 1. Details of Geometry for Case-1

AR	Length (meter)	Diameter (meter)	Flow rate (kilogram/second)	Initial Temp. (Deg. Celsius)	Inlet Temp. (Deg. Celsius)
3.0	1.194	0.398	0.10	30	60
2.5	1.194	0.478	0.10	30	60
2.0	1.194	0.597	0.10	30	30

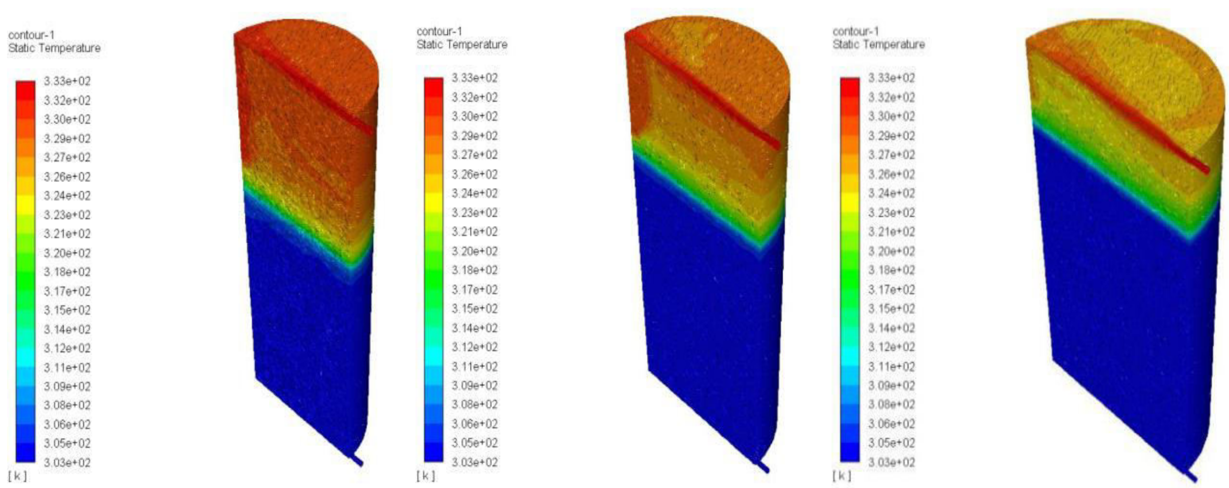


Figure 8, 9 &10. Temperature contour at 500 Seconds for L/D ratio of 3.0 , 2.5 and 2.0

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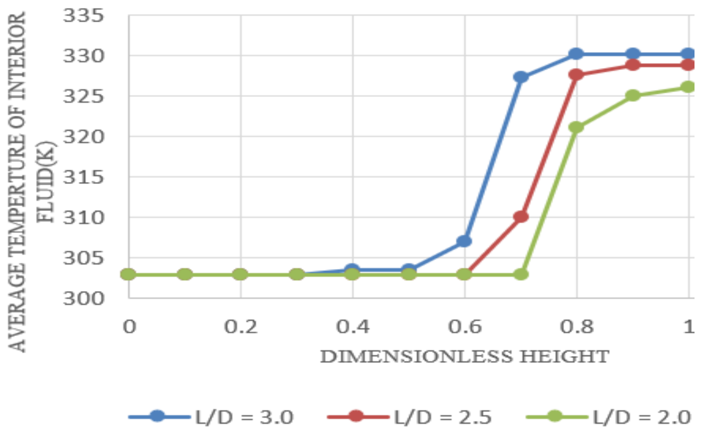

Figure 11. Variation of the average temperature of the fluid against the dimensionless height

Variation of Tank Length by Holding the Diameter as a Constant

In this instance, the length of the stratification tank is altered while the diameter is maintained. Table 2 displays the simulation details for this situation. Increasing the tank's length will also increase the L/D ratio and the volume of the stratification tank.

Table 2. Details of Geometry

AR	Length (meter)	Diameter (meter)	Flow rate (kilogram/second)	Initial Temperature(°C)	Inlet Temperature(°C)
3.0	1.194	0.398	0.10	30	60
2.5	1.194	0.478	0.10	30	60
2.0	1.194	0.597	0.10	30	30

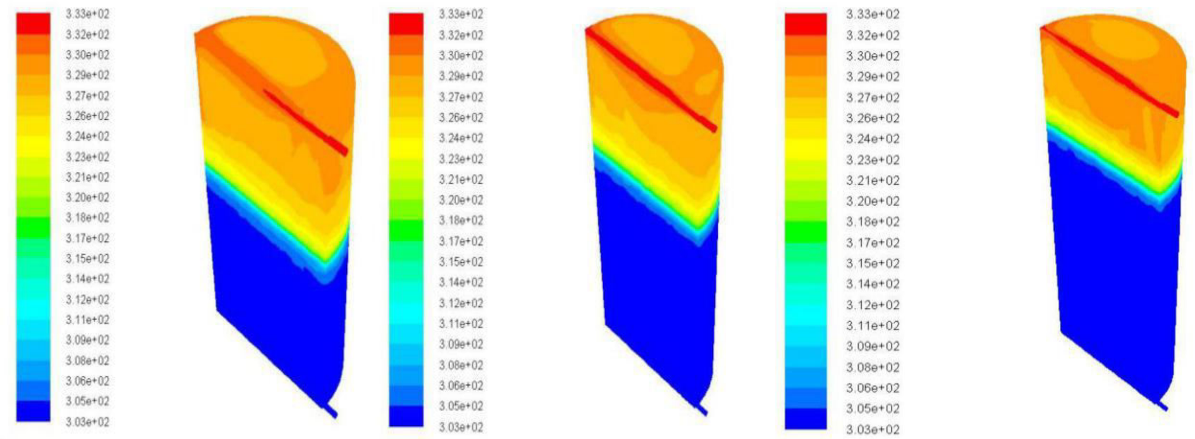

Figure 12, 13 & 14. Temperature contour at 500 seconds for L/D ratio of 2.0, 2.5 and 3.0

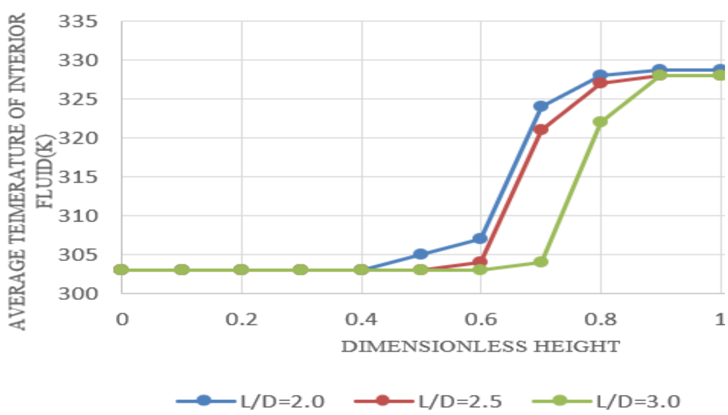

Figure 15. Variation of the average temperature of the fluid against the dimensionless height

Figure 12,13 & 14 describes the temperature contour at 500seconds for L/D ratio of 2.0,2.5 and 3.0 respectively. Figure 5. explains Case I suggests that the tank with a higher L/D ratio shows better stratification than the tank with a lower L/D ratio. Case II the tank with a lower L/D ratio shows a better stratification than the tank having

ISSN 2394 - 9554

a higher L/D ratio. It is established that if the volume of the tank increases in any direction the stratification effect is decreased. Hence over-sizing of the tank leads to de-stratification.

Position of the Intake and Exit Ports' Effects on the Tank's Internal Thermal Stratification

This research has looked at the impact on stratification of different inlet and outflow port positions. The top and bottom walls of the stratification tank's intake and outlet ports are separated from one another differently. Table 3 contains information regarding the simulation.

Table 3. Geometry Details for simulation

Distance of ports	Length (meter)	Diameter (meter)	Mass flow rate (kilogram/second)	Initial Temp (Deg. Celsius)	Inlet Temp. (Deg. Celsius)
0.1	1.194	0.442	0.10	30	60
0.2	1.194	0.442	0.10	30	60
0.3	1.194	0.442	0.10	30	30

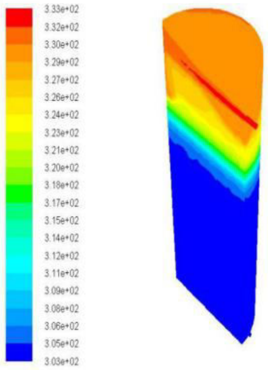

Figure 16. Temperature Contour at 500 seconds for 100 mm from the top and bottom of the tank's inlet and exit ports.

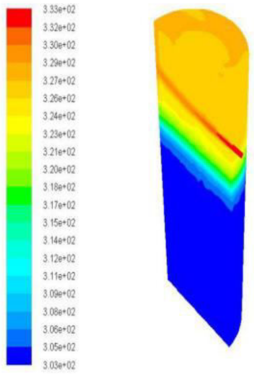

Figure 17. Temperature Contour at 500 seconds for 200 mm from the top and bottom of the tank's inlet and exit ports.

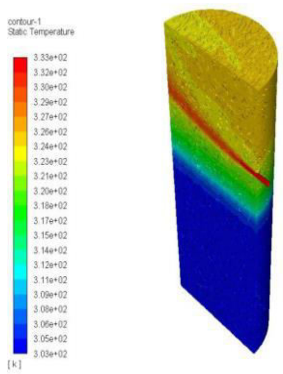

Figure 18. Temperature Contour at 500 seconds for 300 mm from the top and bottom of the tank's inlet and exit ports.

Figure 16, 17 &18 describes the temperature contour at 500 seconds for inlet and outlet port position of various dimensions from reference point. From the Figure 19, shows clear that if the height of both the port increases, the impact of jet momentum is mixing water decreases, and this physical phenomenon of buoyancy on mixing the water increases. At 500 seconds the tank which has the inlet and outlet port separated by a distance length of 100mm from the up & down wall of this tank achieved a higher temperature at the top. This means that the upper layers of the tank reach higher temperatures as the inlet port gets closer to the top and bottom walls.

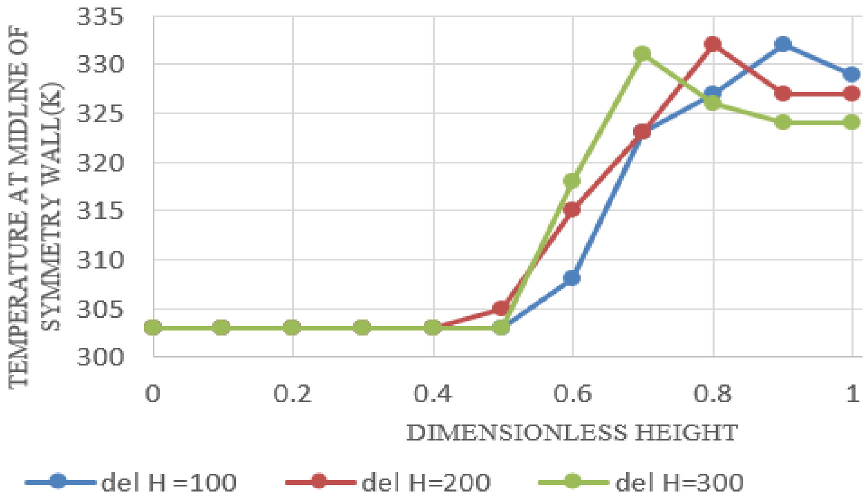

Figure 19. Variation of the average temperature of the fluid against the dimensionless height for varied port locations of 100mm, 200mm, and 300mm for respective boundaries

For a dimensionless height greater than 0.7, the temperature of the tank with inlet and outlet ports at 300mm shows less temperature than the other cases. At the middle of the tank, height between 0.55 and 0.7 of the tank having the inlet and exit port far away from the top and bottom of the wall shows higher temperature. This

 ISSN 2394 - 9554

shows that if the inlet and exit ports are possibly close to the top and bottom surface of the tank, a greater thermal stratification is likely to be produced.

Thermal Stratification and Mass Flow Rate Interaction

By simulating the three instances, the impact of mass flow rate on thermal stratification is investigated (details are presented in Table 4.

Table 4. Geometry Details for the Simulation

Distance of ports	Length (meter)	Diameter (meter)	Flow rate (kilogram/second)	Initial Temp. (Deg. Celsius)	Inlet Temp. (Deg. Celsius)
0.02	1.194	0.442	0.05	30	60
0.02	1.194	0.442	0.15	30	60
0.02	1.194	0.442	0.2	30	30

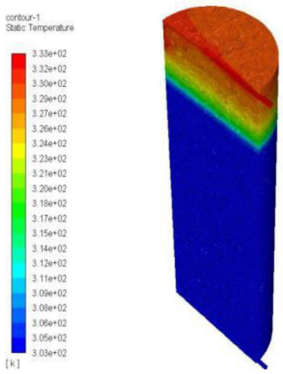

Figure 20. Temperature contour at 500 seconds for 0.05kg/s

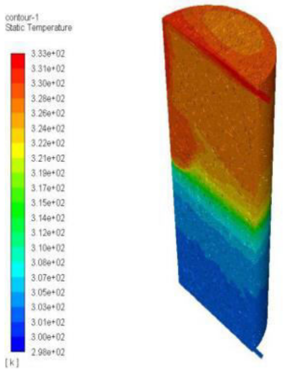

Figure 21. Temperature contour at 500 seconds for 0.15kg/s

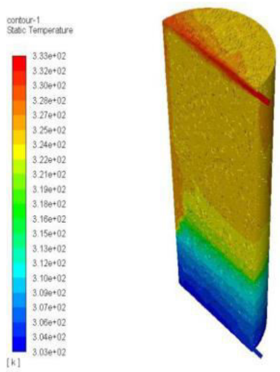

Figure 22. Temperature contour at 500 Seconds for 0.20kg/s

The temperature profile at 500 seconds for flow rate of 0.05 kg/s is shown in Figure 20. For 0.15 kg/s, Figure 21 depicts the temperature contour at 500 seconds, and for a flow rate of 0.20 kg/s, Figure 22 depicts the temperature contour at 500 seconds.

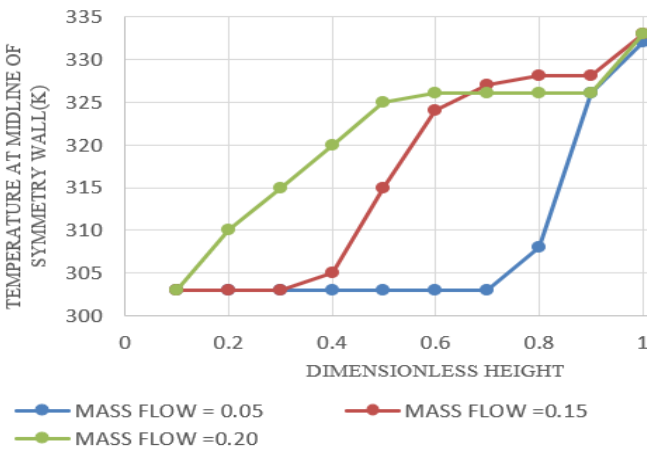

Figure 23. Midline Temperature at Symmetry wall Vs Dimensionless Height for different flow rates

The temperature along the symmetry wall's midline for each example is displayed against dimensionless height based on the simulation findings, as shown in Figure 23. Cold water is removed from the tank and hot water is pumped into it during the charging process. High mass flow rates are accompanied with high thermocline thicknesses. The temperature contour for various mass flow rates serves as proof of this. In comparison to all other mass flow rates, the thermocline thickness is larger at 0.20 kg/s. It's interesting to see that stratification is improved with a mass flow rate of 0.15 kg/s compared to 0.20 kg/s. This results from mixing as a result of increased momentum brought on by an increase in flow rate. Hence conclusion is that adequate flow rate where we can get better stratification at the upper layers, lower the mass flow rate than optimal value leads to more time in achieving the stratification.

CONCLUSIONS

The simulation of L/D ratio influences on thermal stratification and proves that if the volume of the tank is increased, the stratification gets affected. The thermal stratification is improved when the L/D ratio is raised by reducing the tank's diameter. However, the thermal stratification is impacted if the L/D ratio of the thermal stratification tank is raised by lengthening the tank. Hence tank with a lower volume will maintain thermal stratification to a greater extent compared with the tank having a higher volume, hence the over sizing of the stratification should not be done, it will result in destratification.

The findings demonstrate that the thermal stratification tank's inlet should be located close to the top surface of the tank since raising the inlet from the top position lowers the temperature at the tank's top, which results in destratification. The effect of mixing owing to buoyancy will rise as the distance of the inflow port from the top of the tank increases. The results also demonstrate that the stratification inside the tank is adversely affected by an increase in flow rate, whereas momentum diffusion between the hot and cold fluid is boosted. It is found that the best stratification at the upper layer is accomplished by an ideal mass flow rate.

REFERENCES

1. F.J.Oppel, “Computer Simulation of Stratified Storage”, Journal of applied Energy, 1986, 23, 205-224.
2. Anguili li, “Effect of Different Thermal Storage Structures on Thermal Stratification and thermal efficiency during charging”, Journal of Applied Energy, 2018,173, 882-892.DOI: 10.1016/j.solener.2018.08.025
3. T.Bouhal “Numerical Modelling and optimization of Thermal Stratification in hot water storage tanks for Domestic applications”, Journal of Solar Energy, 2017,157, 441-455. DOI: 10.1016/j.solener.2017.08.061
4. Zacher et al “Experimental Study on Effect of Baffles on hot water Storage tanks” Journal of Applied energy, 2003,125, 558-569.
5. Buruk Krusan et al “Effect of Different insulation Geometry on Stratification” Journal of applied Thermal Science, 2018, 125-135. DOI: 10.1016/j.solener.2018.05.019
6. Buruk Krusan et al “Effect of different Positions of Rectangular tank on stratification in the hot water storage tank” Journal of applied Thermal Energy, 2016, 189-196. DOI: 10.1016/j.renene.2017.10.013
7. Jose Monacho et al “Effect of Inlet Devices on stratification of hot water storage tanks”, Journal of applied Energy, 2017, 150,459-465. DOI: 10.1016/j.enbuild.2017.06.012
8. Maria Gasque et al “Effect of Inner lining on Stratification” Journal of applied Energy, 2015,75, 789-795.DOI: 10.1016/j.aplthermaleng.2014.10.040
9. Janne Dragstad et.al “Thermal stratification build-up in hot water tank with different inlet stratifiers”, Solar Energy, 2017,147, 414-425.DOI: 10.1016/j.solener.2017.03.008
10. Shu-hong et.al “Experimental effect of Inlet structure on discharge performance of a solar hot water tank”, International Journal of Low Carbon Techonologies, 2014,790,490-496.DOI: 10.1016/j.enbuild.2013.11.086
11. Dogan Ermedir and Necdet Altuntop “Improved Thermal Stratification with Obstacles placed in Vertical Hot water storage Tank”, Applied Thermal Engineering, 2016,100, 20-29. DOI:10.1016/ j.appl thermal eng.2016.01.069
12. N.M. Brown and F.C Lai “Enhanced Thermal Stratification in Liquid Storage Tank with a Porous Manifold”, Solar Energy, 2011, 1409-1407. DOI: 10.1016/j.solener.2011.03.024
13. Zheng Yang et.al “Comparative Studies of Influence of different Water tank shapes on Thermal Energy storage capacity and thermal Stratification”, Renewable Energy, 2016,85, 31-34. DOI: 10.1016/j.renene.2015.06.016
14. Castel et.al “Dimensionless numbers used to characterize the stratification in water tanks for discharging at lower flow rates”, Renewable Energy, 2010,35,2192-2199. DOI: 10.1016/j.renene.2010.03.020
15. H. Yoo, E.T. Pak, Analytical solutions to a one-dimensional finite-domain model for stratified thermal storage tanks, Solar Energy,1996,56,315-322. DOI: 10.1016/0038-092X(96)89365-0.
16. M.S. Shin, H.S. Kim, D.S. Jang, S.N. Lee, Y.S. Lee, Y.G. Yoon, “Numerical and experimental study on the design of a stratified thermal storage system”, Applied Thermal Engineering, 2004,24, 17-27. DOI: 10.1016/S1359-4311(03)00242-4.
17. C.K. Yee, F.C. Lai, “Effects of a porous manifold on thermal stratification in a liquid storage tank”, Solar Energy,1999, 71,241-254. DOI:10.1016/S0038 092X(01)00043-3

18. Y. Mo, O. Miyatake, "Numerical analysis of the transient turbulent flow in a thermal stratified thermal storage tank", Numerical Heat Transfer, 1996,30, 649-667. DOI: 10.1080/10407789608913863
19. S. Alizadeh, "An experimental and numerical study of thermal stratification in a horizontal cylindrical solar storage", Solar Energy, 1999,66, 409-421.DOI: 10.1016/S0038-092X(99)00036-5
20. H. Yoo, E.T. Pak, "Theoretical model of the charging process for stratified thermal storage tanks", Solar Energy,1993,51, 513-519.DOI: 10.1016/0038-092X(93)90136-C
21. D.L. Savicki, H.A. Vielmo, A. Krenzinger, "Three-dimensional analysis and investigation of the thermal and hydrodynamic behaviours of cylindrical storage tanks", Renewable Energy, 2011, 36,1364-1373. DOI: 10.1016/j.renene.2010.10.011