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Numerical verification for different types of curved baffles as stratifiers in solar thermal storage tank

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Abstract. This paper aims to assist the thermal stratification in hot water storage during the partial discharge water. Three different types of curved baffle have been studied each one placed in the bottom of a rectangular standard conventional tank in order to reduce the turbulence mixing of inlet jet. The purpose of this investigation is to numerically study the impact of the curved baffle within a vertical hot storage tank and compare three different baffle designs to select the best one. A three-dimensional computational fluid dynamic (CFD) model was performed using the commercial software package CFX 18. The numerically simulated tank result was validated against the experiment data. The numerical transient temperature distribution and the flow characteristics were analyzed, and then a comparison was made between the three baffle designs and the calculated performance parameter. The results manifested that the curved baffle has a significant effect for enhancing the thermal stratification at high flow rates. Design C showed the best thermal stratification due to the downward curvature shapes.

1. Introduction

As a time-dependent source of energy, solar energy is not always available when there is an energy demand; this makes use to store the energy. One of the applications is the solar water heater storage tank, which is at most a storage of energy either by latent or sensible. The latter is considered the simplest way for storing due to simplicity and economy [1]. The thermal stratification of thermal energy systems in hot water tanks plays a positive effect for storing the heat energy, which is led to increase the system performance and utilization efficiency. As hot water is used and flows out of the tank, the supply cold water is charged to the tank from the bottom and will mix with the hot water leading to reduce the stratification efficiency, especially at draw off in long time or in high consumption rate. Various researchers studied to enhance the stratification in storage tank during static and dynamic conditions, most of them included the tank geometry, inlet and outlet port positions and inlet stratifiers [2]. The dynamic condition has been the focus of more researches because it is considered the major problem of disintegration stratification. Many researchers placed different types of baffles and obstacles into the hot water tank in order to provide better thermal stratification. Shah and Furbo [3] inserted two types of baffle in a vertical solar storage tank and compared it with a tank without baffle. One of them is a small curved baffle and other is a large flat baffle, both are facing the inlet jet water pipe. Numerical and experimental investigations were performed during different flow rates (1, 5 and 10 l/min) at the discharge mode. The results showed that the small curved baffle enhanced the stratification by redirecting the flow back to the bottom of the tank and allowing it to spread. Moreover, the large flat baffle plate was the best one with thermal stratification because it allowed the jet to impinge on the baffle surface while not penetrating deep into the tank. Zachar et al. [4] improved the design proposed by Shah and Furbo by studying flat baffles during the charging and discharging modes, two flat horizontal baffles were placed near the inlet and outlet port in the vertical storage tank. According to their study, the flat baffle improved the stratification even at high flow rates reached (10 l/min). Altuntop et al. [5] presented numerically the effect of an obstacle in thermal stratification of a vertical solar storage tank during the dynamic mode. Different kinds of obstacle were placed at the bottom of the tank. The inlet cold water pipe is in a horizontal position. They found that the cone and flat ring obstacle types having an opening in the middle provide better thermal stratification. Erdemir and Altuntop [6] analyzed the thermal stratification of a vertical mantled hot water tank by the insertion of obstacles. Four types of obstacle were tested experimentally. They obtained that placing the obstacle inside the tank has a significant effect in improving the thermal stratification, especially when placing them at a distance between y=0.2 and y=0.3 m from the bottom of the tank. Moreover, the ring obstacle type with an opening in the middle was the best for thermal stratification. Wang et al. [7] investigated the thermal stratification of a hot storage tank at the discharging process. The tank with a novel inlet placed at its entrance was tested experimentally and numerically. The novel equalizer consists of three cavities perforated in one side, overlapping with each other. The result indicated a high performance of storage tank with inlet equalizer and it was more efficient when compared with the direct inlet port and three layers of perforated baffles. Yang and Shue [8] carried out a numerical simulation to enhance a large solar horizontal storage tank by several stratification designs during the same time of charging and discharge modes. Partition flat baffles were inserted inside tank vertically. They concluded that placing one partition in the middle of the tank increases the solar fraction by 7-8% compared with no baffled tank. Moreover, by adding one more partition, the system efficiency can be further increased by about 2%. Aviv et al. [9] reported a horizontal hot storage tank with a side inlet jet during the discharge mode to reduce the flow turbulence mixing. An experimental and numerical study was done for different flow rates. It was observed that at a high flow rate 7 l/min of discharging, the cold-water jet impinged on the opposite side wall of the inlet jet, resulting in an intensive mixing in this side of the tank. It was concluded that placing a deflector at the entrance improves the thermal stratification performance. Bouhal et al. [10] numerically studied enhancing the thermal stratification in two vertical solar domestic storage tanks during the discharge mode. The first tank has side inlet and outlet pipes, and the second has vertical inlet and outlets pipes. The effect of the flat baffles positions within a tank was investigated in the first tank, while the inclination baffle was studied in the second tank. It was concluded that the best thermal stratification was by placing two baffles located at the middle and top of the first tank, while the baffle with 30 degree inclination gave the best performance in the second one. Many authors still research for the enhanced stratification of storage tank during the dynamic mode by any beneficial way. However, some of them do not take into consideration the simple manufacturing and cost of straifiers, especially for domestic storage tanks. Such kind of the diffusers sometimes is difficult to provide it due to its cost and difficulties in manufacturing [3]. Moreover, most of studies in vertical tanks take into consideration the position of the inlet water jet at the bottom of the tank. However, the side inlet pipe is desirable in many applications of storage tanks, especially in tanks that are based directly on the floor. Hence, the aim of this work is to conduct a numerical verification by using a commercial CFD package to examine three simple designs of curved baffles placed at the entrance of the tank, since it is expected to restrict the inlet fluid at the bottom of the tank and prevent it from spearing, and thus it leads to decrease the turbulence mixing. The performance of the three tanks with baffles will be compared with the standard conventional tank, which have no baffle. The CFD commercial code CFX.18 is used in order to carry out the numerical simulations and to explain the numerical observations and results. The CFD results will be validated against experimental results.

2. Numerical Investigations

2.1 Storage tank physical models and meshing

A standard configuration water tank with a side inlet was investigated by means of computational fluid dynamics (CFD). The rectangular tank has dimensions of height 0.9 m and square base. The ratio of height to base (H/D) is 2, which is considered the favorite design to improve the thermal stratification [11]. Thus, the volume is approximately 180 L^3, which is the acceptable design required for SDHW applications. The water inlet and draw off pipes are located at the lower and upper side of the tank, respectively, having the inner and outer diameters of 22 and 25 mm, respectively. In order to further improve the stratification, three different curved baffles designs were studied, each one placed at the bottom of the same standard tank deigned, as shown in figure 1. The baffles position in the tank with the dimensions is given in Table 1. All dimensions are similar in each tank except the curvature radius. In the models, only a half of the tank was modeled. This is because symmetry is assumed in the center plane of the tank. This simplification was made in order to reduce the total number of grid elements in the numerical mesh. The model was meshed by commercial CFX 18 using unstructured tetrahedral. The mesh dependency was tested before the simulations. The final mesh obtained consists of 1421434 nodes and tetrahedral 1025745 for the conventional standard tank. Figure 2 reveals the mesh of the geometry.

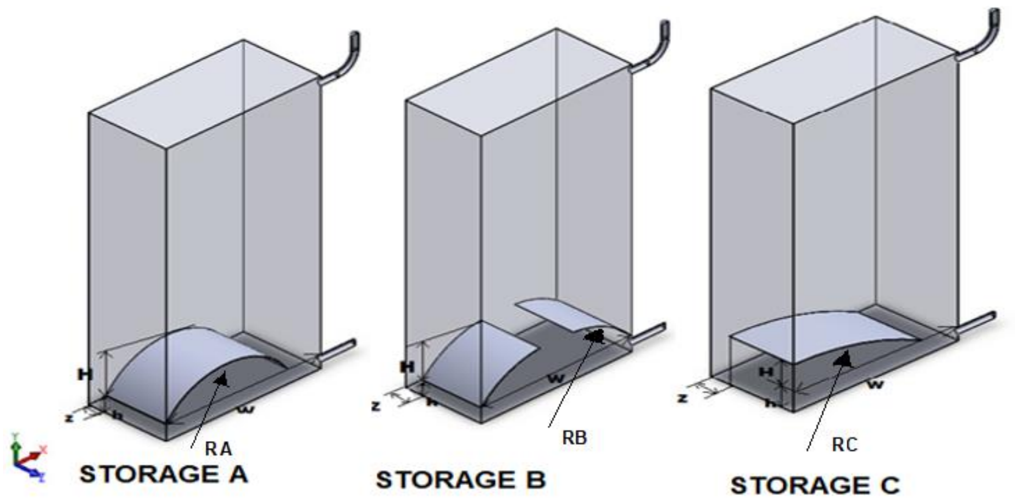


Figure 1. Details of the 3D Computational models with baffle position (symmetric)

Table 1: Baffles dimensions.

Symbol	W	e	o	H	h	z	RA	RB	RC
Dimension (mm)	450	15	100	100	50	50	205	250	662

2.2. Governing equations.

The governing equations of the problem are the continuity, the momentum and the energy equations. The equations are written in Cartesian coordinates as given below:

The continuity equation:

$$\frac{\partial \rho}{\partial t}+\sum_{i=1}^{3}{}' \frac{\partial}{\partial xi}(\rho ui)=0 \tag{1}$$

The momentum equation:

$$\frac{\partial \rho Ui}{\partial t}+\sum_{j=1}^{3}{}' \frac{\partial}{\partial xj}(\rho Uj\; Ui)= -\frac{\partial P}{\partial xi}+\sum_{j=1}^{3}{}' \frac{\partial}{\partial xj}\left(\mu eff \left(\frac{\partial Ui}{\partial Xj}+\frac{\partial Uj}{\partial Xi}\right)\right) + SM \tag{2}$$

The energy equation:

$$\rho c_p \frac{\partial u_i T}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i} - \rho \overline{u_i' T'}\right) \tag{3}$$

Where,

k is the thermal conductivity.

SM is the sum of body forces.

μeff is the effective viscosity accounting for turbulence.

$$\mu eff = \mu + \mu t \quad (4)$$

Where, μt is the turbulence viscosity, which is linked to the turbulence kinetic energy and dissipation via the relation:

$$\mu t = C\mu .\ \rho .\ \frac{k^2}{\varepsilon} \quad (5)$$

The governing equations mentioned above were solved taking into account the following assumptions:
1- Three dimensional flow, unsteady state.
2- Constant water property except the density.
3- Turbulent flow, since the Reynolds number (Re) corresponding to the inflow velocity based on the inlet pipe diameter is 14000, and for Reynolds number over 4000, the flow is considered turbulent (12).
4- Adiabatic tank walls mean that no heat loss and no heat flow within the wall (3).

2.3. Model simulation.
A simulation model of the flow in the tank was developed using the CFD commercial code CFX 18 to solve the flow and energy equations. Turbulence was modeled using RANS approach. The modeling parameters of the storage tanks are as follows:

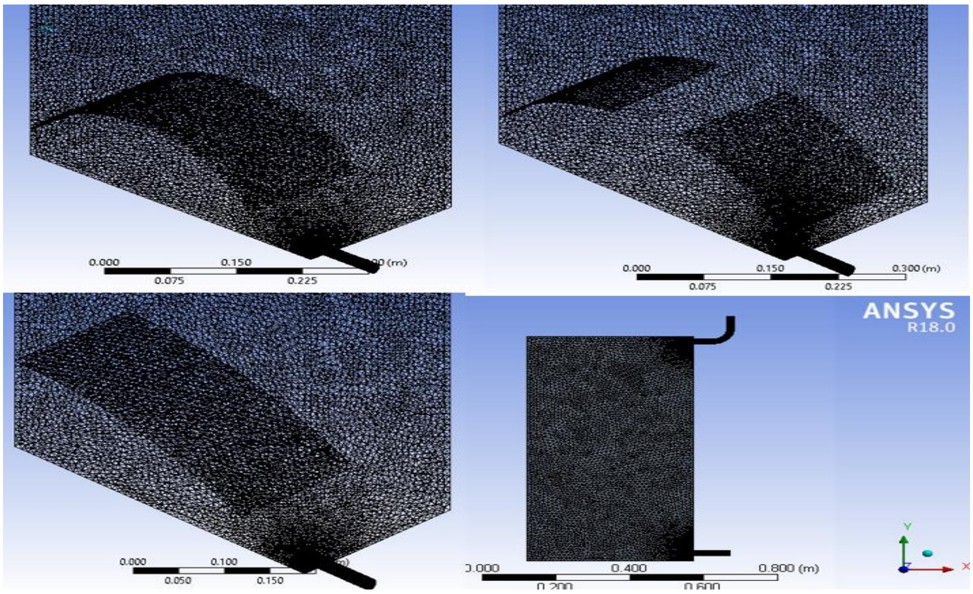


Figure 2: Tank view meshing showing the enlarged baffles inside the three types of tank and front side of tank

- Full buoyancy model is activated with the existence of hydrostatic tank pressure.
- Constant water properties, except that the density which is defined as polynomial functions with temperature, as given by the following equation 6 (13).

$$\rho = -3.784 \times 10-3\ T2 + 2.010\ T + 733.5 \quad (6)$$

- Time step is 0.5s, after sensitivity to time step has been done.
- The RNG k- ε models were used to determine the simulation.
- The convergence criteria were set to root-mean-square with residual and conservation target of 10^{-4} and 10^{-3}, respectively.

3. Description of the Experimental System.

The experimental setup is illustrated in figure (3) depicting the studied rectangular, vertical tank, which has the same dimensions and design described in the solid models. The tank is made of galvanized steel and insulated with 10 mm fiber glass wool of thermal conductivity k=0.043 W/m °C, in order to reduce the heat loss. There are passage pipes in the opposite inlet and outlet pipes, which are connected with a thermostatic electric water heater and a recirculation pump in order to supply the tank with the mixed hot water. ZYIA flowmeter was employed to measure the inlet water flow rate with accuracy ± 0.15%. A thermocouple tree of 11 thermocouples was used to measure the transient vertical temperature distribution in the tank. The thermocouples tree is located in a half way between the symmetry axis and inlet jet side. Many of the thermocouple props are located in the middle of tree. One thermocouple is located in the inlet pipe to measure the cold inlet water temperature. All thermocouples are of type K calibrated and connected with a data acquisition unit BTM-4208SD digital type, and the temperature values were measured every 50 s during the 50% of discharging. The acquisition unit is connected to a personal computer. The experimental cold water inlet temperature is about 30°C, the tank initial temperature is 50.5°C and the ambient temperature is 27°C in a clear day.

4. Results and Discussion.

In the present study, a numerical simulation is carried out and validated against experimental result from a conventional standard tank studied. As previously described, three curved baffles were used in order to find the best one and optimize its curvature. Thus, a three dimensional section of water tank temperature measurement, contours and streamlines, was extracted to predict the performance of stratification inside a storage tank. Moreover, Richardson number, Stratification number of the tank was used as indicators to stratification efficiency.

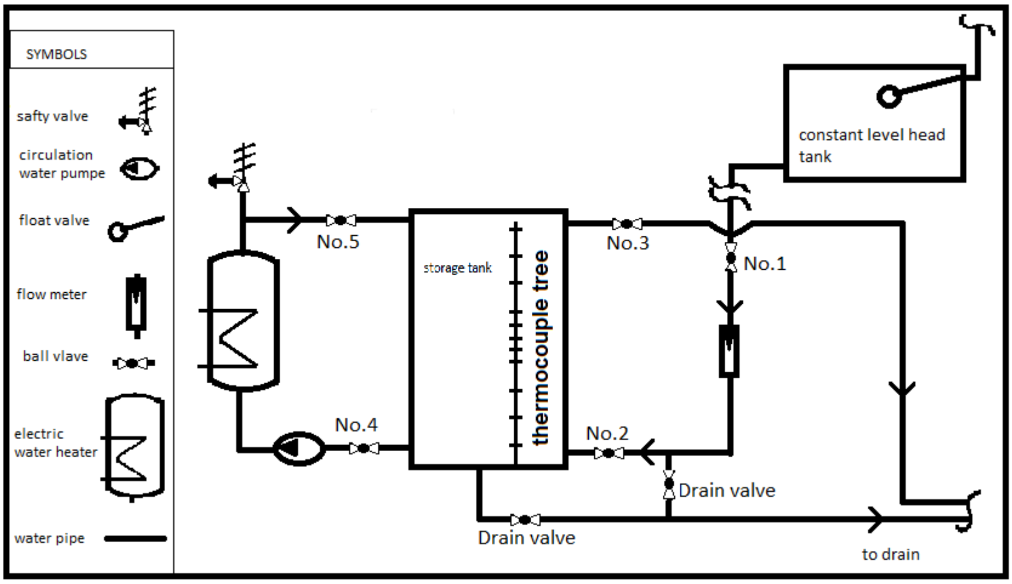


Figure 3. Schematic view of the experimental system.

The partial discharge mode with a total duration time of 7.5 min was studied. In all situations, the tank initially contains a body of hot mixed water at a temperature of 50°C, the tank is discharged with an inlet water temperature of 30°C and a flow rate of 12 l/min. This flow rate, which is considered a high flow rate used in the domestic application, gives the greatest possible amount of mixing. This consumption representing about one half of the total water volume in the tank was discharged.

4.1. Model validation.

The experimental results were validated with the numerical results for a conventional standard tank. Figure 4 manifests the transient temperature distribution for three elapsed times during the partial (50%) discharge. This figure clarifies the good agreement between the experimental and numerical temperature distribution in the observation, and the relative error is shown in the Table 2.

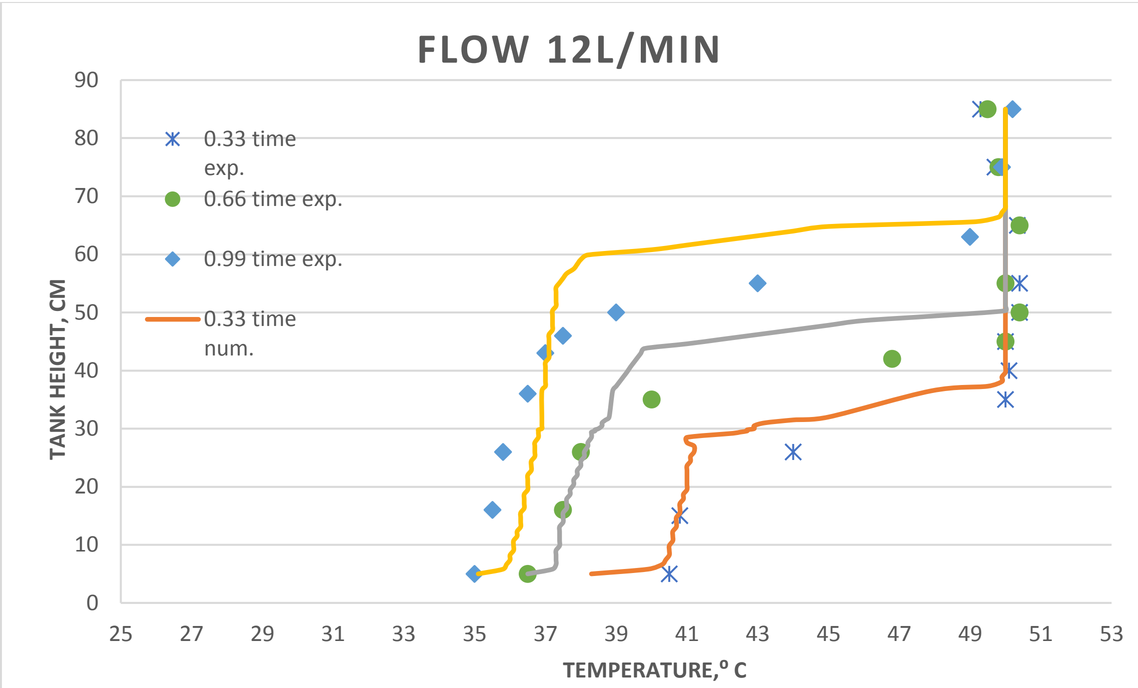


Figure 4. Temperature distributions during three times of partial discharging process.

4.2. Temperature field.

Before the verification of the baffled tank cases, a conventional unstratified tank must be studied to find out the behavior of the cold inlet jet during the transient dynamic mode. Figure 5 evinces the temperature couture during a certain time while drawing off the hot water.

Table 2. The relative error at 0.99 time of discharging

Probe number	Experimental temperature (°C)	Experimental position (cm)	Numerical temperature (°C)	Numerical position (cm)	Relative error (%)
1	35	5	35.1	5	0.99
2	35.5	15	36.3	14.7	0.285714286
3	35.8	25	36.7	25.2	2.253521127
4	36.5	35	36.9	36.5	2.51396648
5	37	40	37	39.7	1.095890411
6	37.5	45	37.1	45.4	0
7	39	50	37.2	50.3	1.066666667
8	43	55	37.4	55.1	4.615384615
9	49	65	45	64.8	13.02325581
10	49.9	75	50	75.3	8.163265306
11	49.5	85	50	85	0.200400802

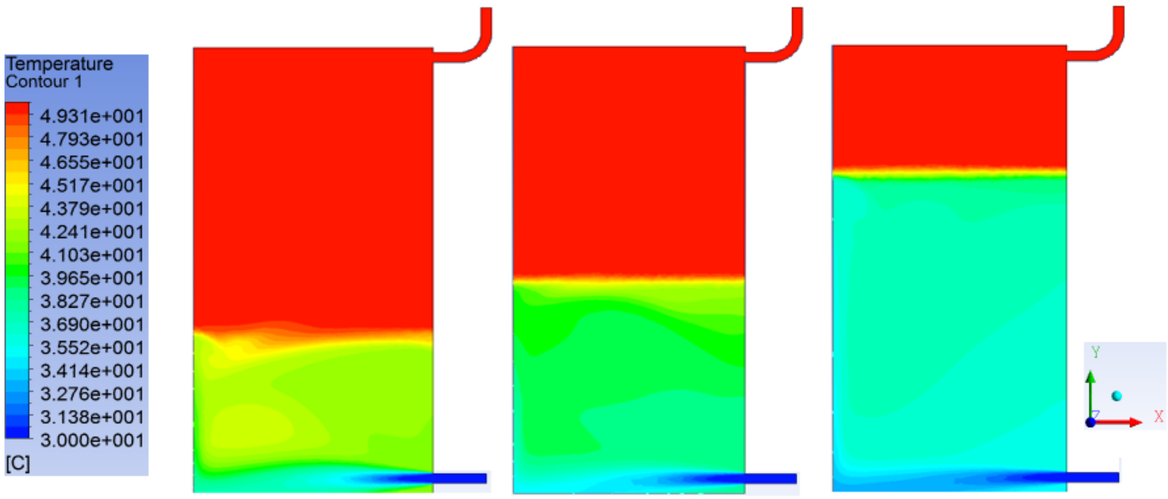


Figure 5. Temperature distribution of conventional standard tank model in symmetry plane after consumption rates; **left**: 12.5 %, **middle**: 25 % and **right**: 50 % of the tank volume.

It is evident that the momentum of the cold incoming water jet causes a great mixing rate in the tank. Although the inlet water jet loses some of the momentum inside the tank due to the tank pressure head and shear forces, it is clear that the cold jet is penetrated through the static fluid horizontally till it impinges on the opposite tank wall to the jet due to the high inlet jet velocity. The water rose beside the opposite wall and dragged down due to the water gravity; hence, a vortex is produced on the left side of the tank. With the time progressing, as a hot layer raised, the cold water jet still being raised at the left side of the tank and causes more effective mixture between the separated layers leading to more rate of recirculation. This indicates more mixing occurred in the conventional tank even with time. In comparison with the baffled tank, figure 6 demonstrates the less mixing between the stored water and the inlet jet in a curved tank. The effect of the curved baffle is to reduce the mixing rate by restricting the cold water at the bottom of the tank. Generally, it depicts that common phenomenon for all curved baffle. However, it seems that the temperature couture in tank C illustrates an enormous improvement of thermal stratification.

4.3. Flow field

Figure 7 displays the velocity streamlines of the mean velocity in three dimensions with a complex phenomenon for the flow field inside the baffled tanks. It is clear that the high velocity of the stream exists at the entrance of the jet to the tank, giving a chance for a high mixing rate to occur at the bottom of the tank. The main stream bulk of the inlet jet, which lies in the middle of the tank floor, flows towards the opposite side wall and impinges on it, so the velocities are slightly reduced. The stream lines also indicate that the flow is divaricate due to the impingement effect. Part of the stream bulk is restricted inside the baffle and gives

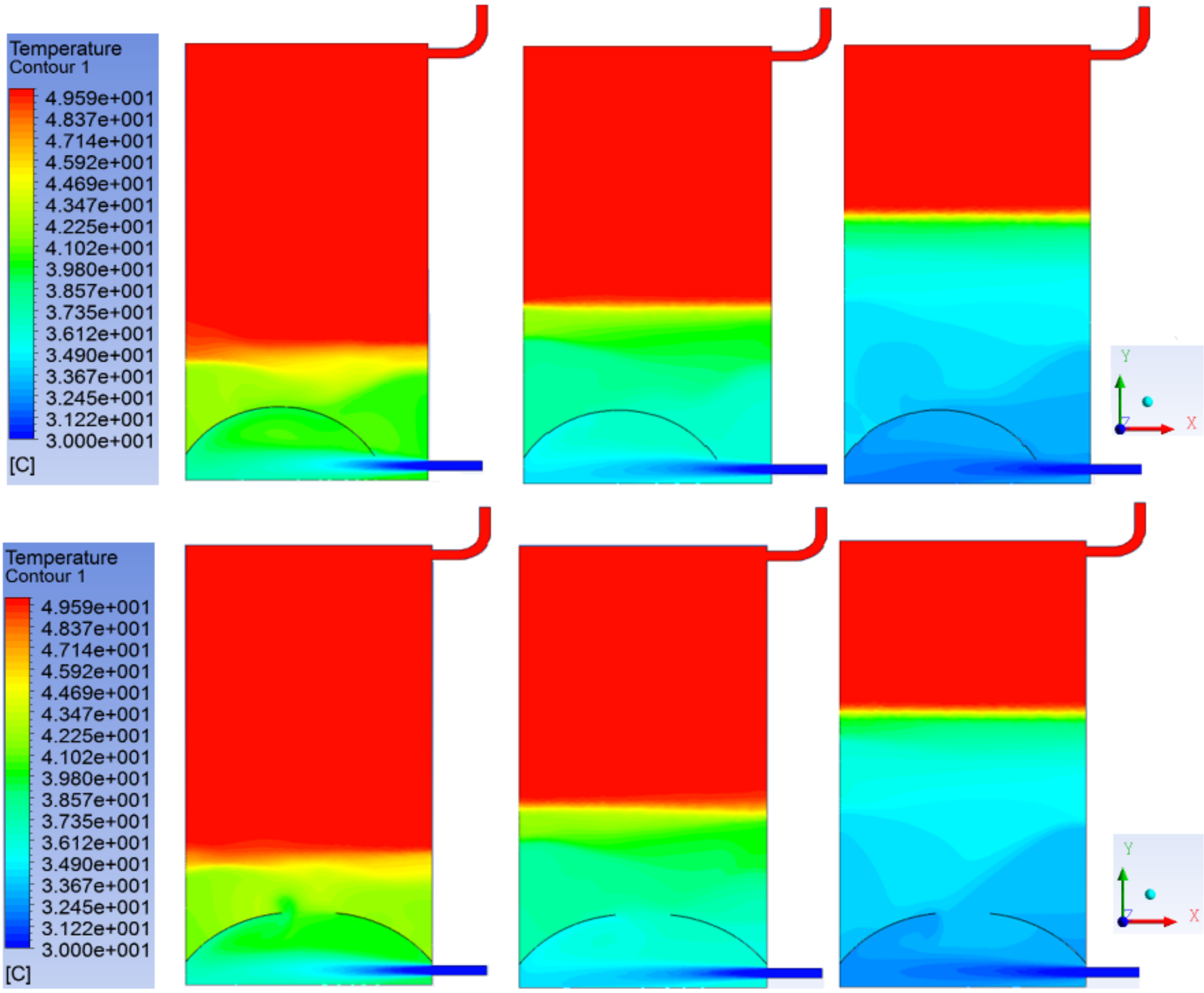
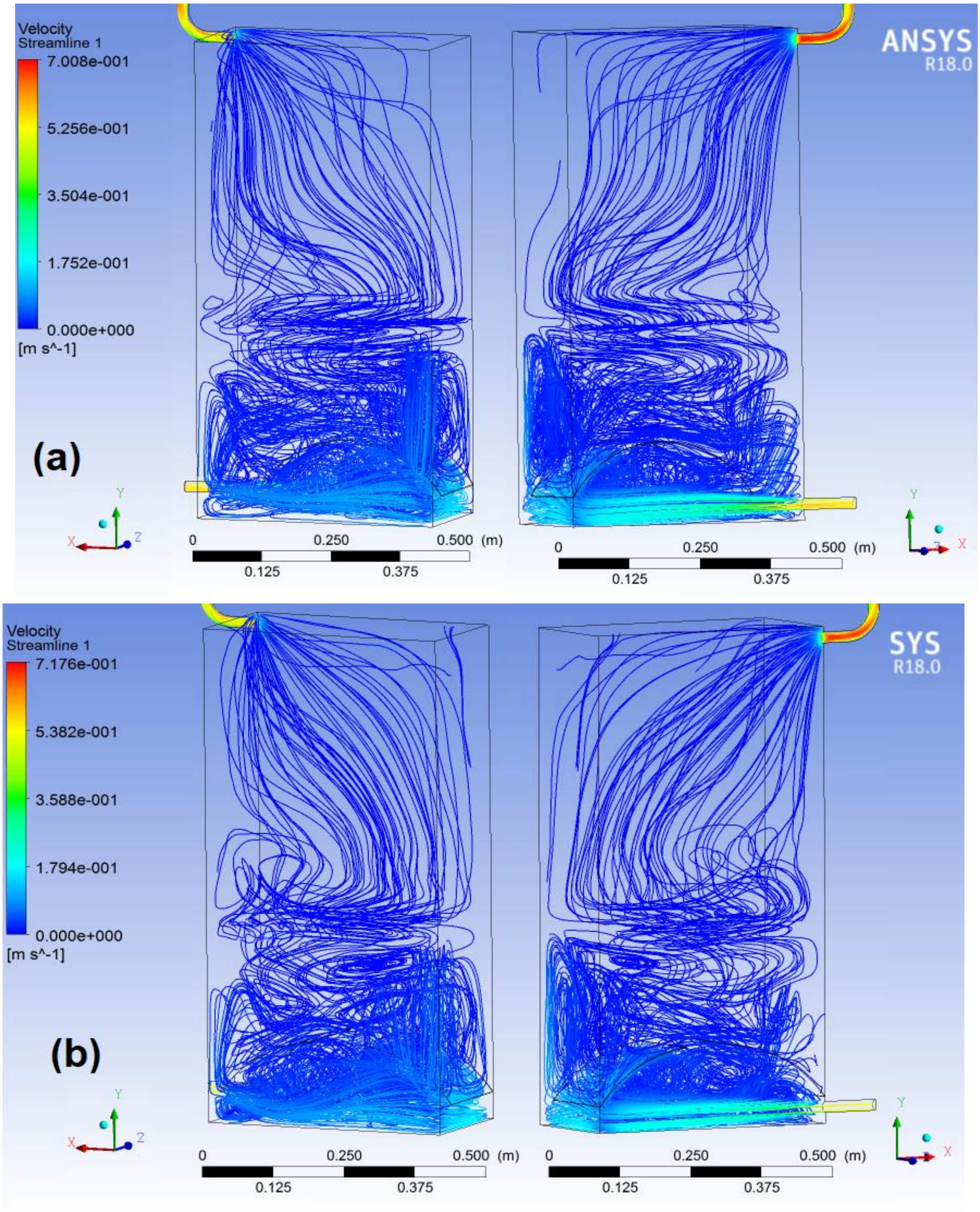


Figure 6. Temperature distribution of tanks models in symmetry plane, from above to bottom: tank A, tank B and tank C, after consumption rates; **left**: 12.5 %, **middle**: 25 % and **right:** 50 % of the tank volume

a complex recirculation patterns confined between the baffle up side and the tank floor in down side, that the main stream flow is also restricted. In the rear view of the tank as shown in the left side of figure (7a), it is obvious that the other part of the high velocity bulk streamlines moves towards the lateral wall side and impinges on it. The effect of this wall leads the flow to path beside it, and finally the flow forms a complex circulation lying just above the baffle. Moreover, at the side opening baffle (Z), it is clear that some of the high stream velocity leave the baffle edge from a large close circulation lies above the baffle near the opposite side wall of the inlet jet. The same flow behavior is noticed in the tank B, as viewed in figure (7b). The effect of the opening the baffle in the middle of tank B is insignificant, that is some of the restricted flow under baffle tend to escape through this opening. In the tank C, the conditions differ as shown in fig (7c) from the previous two cases in that all of the streams leaving the baffle do not rise up but move beside the lateral wall of the tank and finally, the closed circulation ends and becomes closer at the bottom of the tank. From the above analysis, it's obvious that in the semi hemispherical shaped baffles in tank A and B, the baffle shape is started in upward arch shape that facilitates the escape of some rapid fluid flow up at the edge of the baffle and causes a mixing near the hot water layer. In the tank C, the downward arched baffle is a cause of preventing flow from rising up and maintaining the exit water flow from the baffle at the bottom of the tank.


Velocity
Streamline 1
7.008e-001
5.256e-001
3.504e-001
1.752e-001
0.000e+000
[m s^-1]
(a)
ANSYS
R18.0
0
0.250
0.500 (m)
0.125
0.375
Velocity
Streamline 1
7.176e-001
5.382e-001
3.588e-001
1.794e-001
0.000e+000
[m s^-1]
(b)
SYS
R18.0

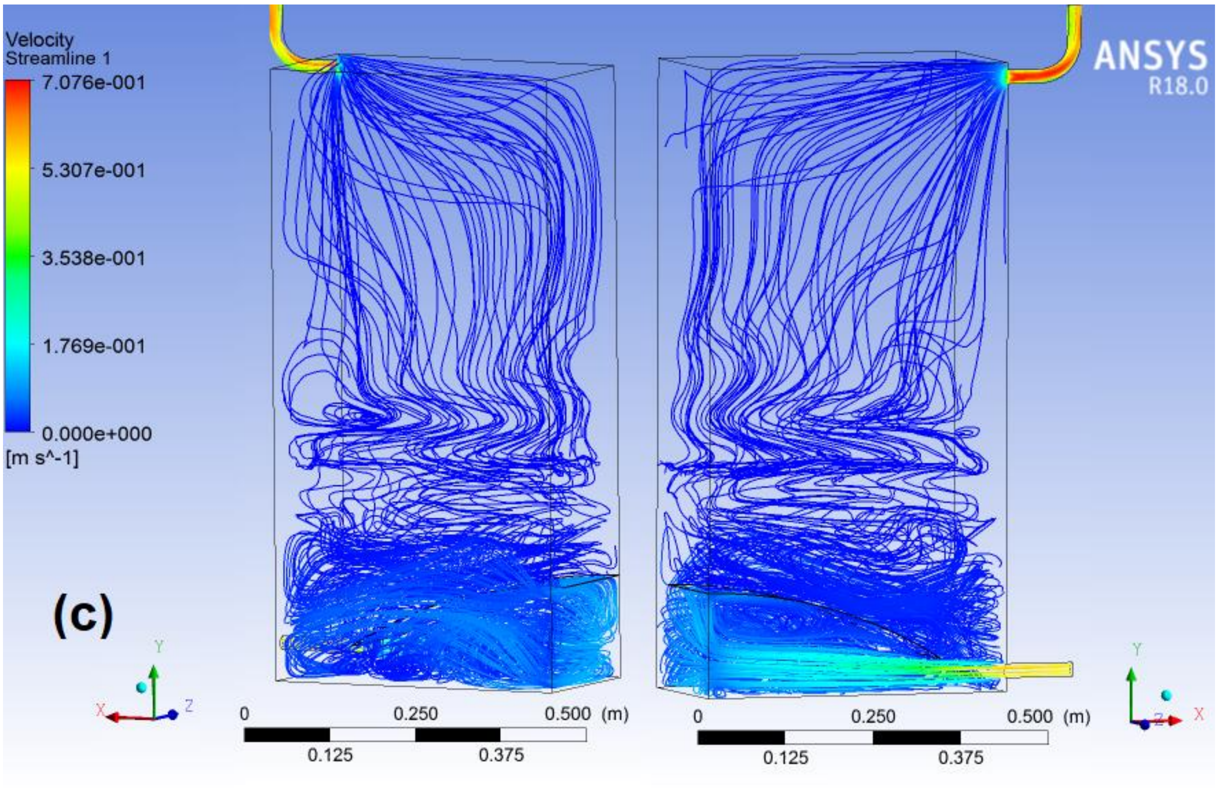


Figure 7. Velocity stream line of tanks models after 1/4 of tank volume draws off; **a)** tank A, **b)** tank B and **c)** tank C model. **Right:** front view and **Left:** rear view

5. Stratification Performance Testing

In order to verify the performance of the designed baffles used in the numerical simulation given previously, two stratification performances were tested, namely the Richardson number and Stratification number as describe below.

5.1. Richardson number

It is an important dimensionless parameter that indicates the level of stratification in the thermal storage tanks (12), it represents the ratio between the buoyancy and the inertial forces as given in Eq. (7):

$$Ri = \frac{g\beta H(Ttop - Tbottom)}{V^2} \tag{7}$$

Where, **Ttop** and **Tbottom** are the mean temperature at the top and bottom of the storage tank, respectively. A beneficial thermal stratification can be realized when the value of Ri number is higher than one depending on the case under consideration. Figures 8 compares the evolution of Richardson number for the four tank models as a function of volume draw off during the partial discharging. As observed, a large Richardson number is obtained at the end of the discharge process which indicates that the mixing rate is reduced. A smaller value of Richardson number is obtained for the conventional tank (Ri= 0.185), thus implying the mixing forces are more pronounced. In tank C the rate of mixing reduces comparing with others and Richardson number reaches (Ri= 0.235), since the mixing force is still a dominated factor due to the selective conditions for this test.

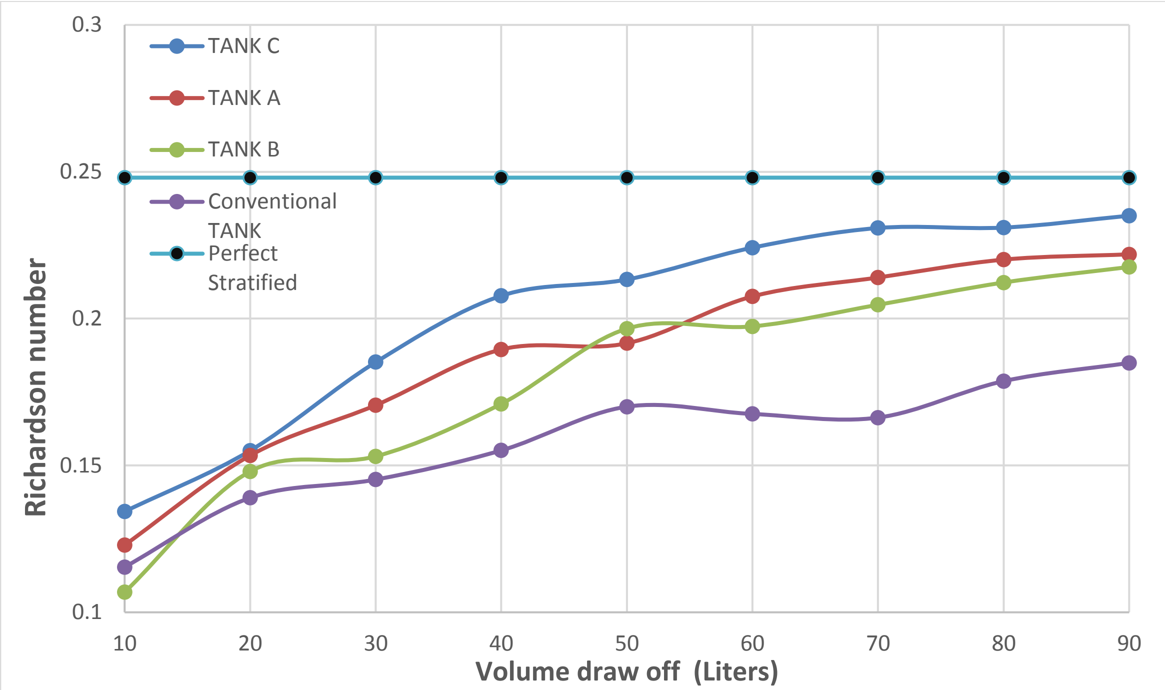


Figure 8. Evolution of Richardson number (Ri) for all curved tanks and conventional standard tank models during draw off water.

5.2. Stratification number

This important correlation gives the detailed information on the development of thermal stratification. Also, it is effective for the evaluation of the thermal behavior of the storage tank during the discharging process [14]. This number was defined by **Fernandez-Seara et al. (2007)**. They expressed it by the ratio of the mean of the transient temperature gradient to the maximum mean temperature gradient for the dynamic processes, as given in Eq. (8):

$$\mathbf{Str(t)} = \frac{(\frac{dT}{dy})t}{(\frac{dT}{dy})max} \quad (8)$$

Where:

$$(\frac{dT}{dy})t = \frac{1}{J-1}\left[\sum_{j=1}^{J-1}\left(\frac{Tj+1-Tj}{\Delta y}\right)\right] \quad (9)$$

And,

$$\left(\frac{dT}{dy}\right)max = \frac{Tmax-Tin}{(J-1)\Delta y} \quad (10)$$

Where, J is the number of nodes.

The stratification efficiency is linearly dependent on the thermal gradient of the storage tank, and the increasing in the thermal gradient results in an increase in the stratification efficiency [14]. Figure 9 elucidates that the stratification efficacy in tank C reached to the highest value approaching 0.94. The following tanks stratification efficiency reached to 0.87 and 0.84 in the tank A and tank B, respectively at 80 L of volume draw off. The latter tanks have a similar behavior of increasing rate in the thermal stratification efficiency followed by a gradual decrease after 80 L draw off. The stratification of the conventional standard tank has less efficiency that reached to 0.53 at the end of discharge time.

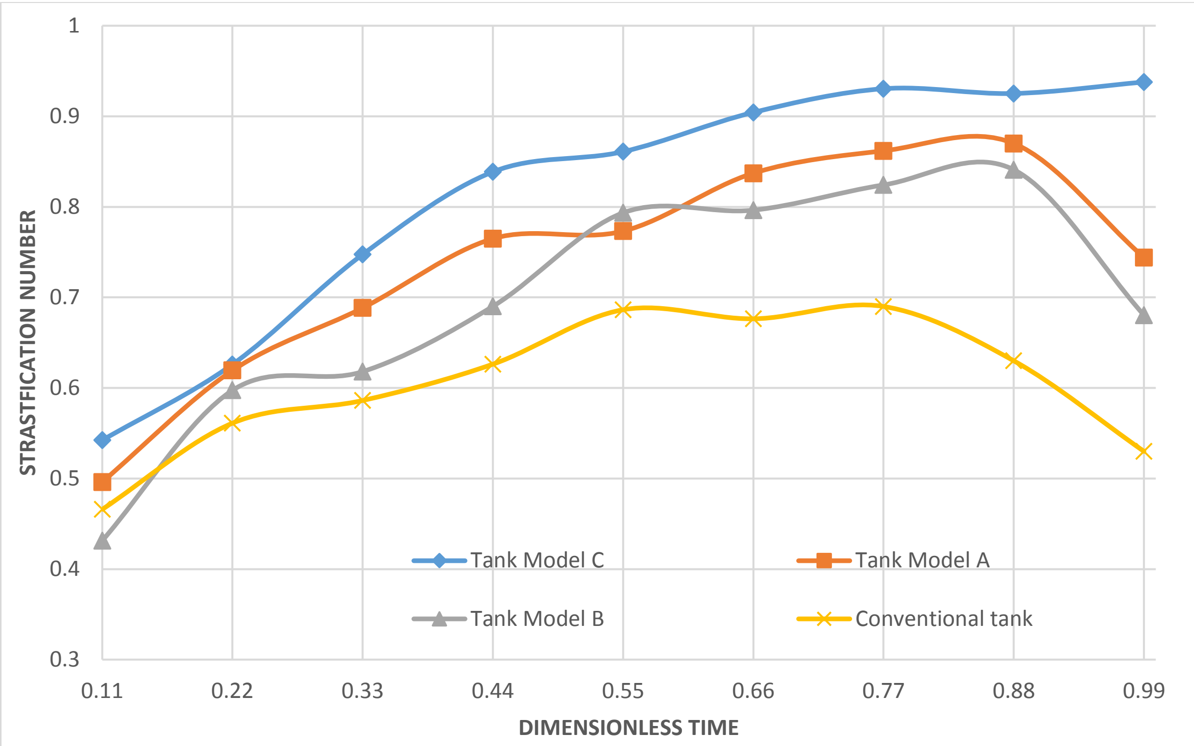


Figure 9. Evolution of stratification number for all curved tanks and conventional standard tank models during draw off water.

6. Conclusions

Thermal mixing has been verified numerically in a vertical solar storage tank with a side inlet jet. The conventional tank was examined with a new design by the insertion of a curved baffle fixed near the bottom of it. Three baffle designs were suggested and verified numerically in CFD model by CFX 18 commercial program. A set of performance indicators were defined to carry out this CFD numerical performance assessment, such as temperature and streamlines contours, Richardson and stratification numbers. The following conclusions are obtained:

1- The numerical investigation showed that the curved baffles assist the reduction of the inlet jet momentum by spreading the jet, forming a close circulation under the baffle area, and resulting in less mixing within the tank.
2- Numerical simulation results represented by temperature field and flow field manifested that the curved baffle in the tank C model gives the best performance due the downward curvature baffle designed which permits the inlet jet from upward to the other layers of the tank.
3- The simulation results evinced a good agreement with experimental data for the conventional standard tank.
4- The performance parameter indicates a higher Richardson number and stratification efficiency that are 0.235 and 0.95, respectively, which are obtained in tank C.
5- The new design using the downward curvature baffle gives an optimum procedure for the selection of the type of the surface to be used for such application.

These findings are very helpful in predicting the behavior of the vertical water storage tank with a side inlet jet for the discharged mode. They help to give a consideration for modifying the curved baffle in future work.

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Nomenclature

V	- Inlet jet velocity	(m/s)	
T	- Temperature	(C)	
Tin	- Inlet temperature	(C)	
H	- Length of the tank	(mm)	
h	- Baffle high from the base tank	(mm)	
R	- Baffle curvature radius	(mm)	
W	- Tank base length	(mm)	
Z	- Baffle side span	(mm)	
ρ	- Density, kg/m^3		
g	- Gravitational acceleration	(m/s^2)	
β	- Thermal expansion coefficient	(1/C)	
Re	- Reynold number		
Ri	- Richardson number		
Str	- Stratification number		
CFD	- Computational Fluid Dynamics		

References

[1] Reza A and Tabrizi S 2018 Numerical and experimental study of inlet-outlet locations effect in horizontal storage tank of solar water heater *Sustainable Eng. Techno. and Assess.* **25** 181-190.

[2] Shaarawy 2014 Numerical Analysis of Thermal Stratification in Large Horizontal Thermal Energy Storage Tanks *Master's Thesis* McMaster, University, Hamilton, Canada.

[3] Shah and Furbo 2003 Entrance Effects in Solar Storage Tanks *Sol. Energy* **75** 337–348.

[4] Zachar, Farkas and Szlivka 2003 Numerical Analyses of the Impact of Plates for Thermal Stratification Inside a Storage Tank with Upper and Lower Inlet Flows *Sol. Energy* **74** 287–302.

[5] Altuntop N, Arslan M, Ozceyhan V and Kanoglu M 2005 Effect of Obstacles on Thermal Stratification in Hot Water Storage Tanks *Appl. Therm. Eng.* **25** 2285–2298.

[6] Erdemir D and Altuntop N 2016 Improved thermal stratification with obstacles placed inside the vertical mantled hot water tanks *Appl. Therm. Eng.* **100** 20–29.

[7] Wang Z, Zhang H, Dou B and Zhang H H G 2017 The thermal stratification characteristics affected by a novel equalizer in a dynamic hot water storage tank *Appl. Therm. Eng.*, PII: S1359-4311(16)33290-2

[8] Ru Y and Geng-Yi L 2015 Numerical simulation study for the performance of a large solar hot water system with horizontal storage tank ASME ES2015-49828.

[9] Aviv A, Morad S, Ratzon Y, Ziskind G and Letan R 2009 Experimental and Numerical Study of Mixing in a Horizontal Hot-Water Storage Tank *ASME J. Sol. Energy Eng.***131** 031004.

[10] Bouhala T, Fertahib S, Agrouaza Y, El Rhafikic T, Kousksoua T and Jamilb A 2017 Numerical modeling and optimization of thermal stratification in solar hot water storage tanks for domestic applications: CFD study *Solar Energy* **157** 144-455.

[11] Burak K and Korhan Ö 2017 Effect of rectangular hot water tank position and aspect ratio on thermal stratification enhancement *Renewable Energy* **17** 30974-6.

[12] Castell A, Medrano M, Sole C and Cabeza L 2010 Dimensionless numbers used to characterize stratification in water tanks for discharging at low flow rates *Renewable Energy* **35** 2192–2199.

[13] Brecht B 2017 Tank sizing to minimize environmental impact in a renewable energy context *PhD Thesis*, Arenberg Doctoral School.

[14] Olfa A, Hatem M and Philippe B 2015) CFD analysis of thermal stratification in domestic hot water storage tank during dynamic mode *Build Simul.* 12273-015-0216-9.