# Study the Effect of Heat Losses on the Thermal Stratification in Cylindrical Hot Water Storage Tank

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## Abstract:

Storage tank with different hot water inlet flow rate (4, 6, 8 and 10) L/min and with insulated and uninsulated wall surface is studied experimentally and numerically.
The objective of the investigation is to show the effect of heat losses from the tank to the surrounding on the thermal stratification within the water storage tanks and to evaluate the possible enhancement in the thermal performance of solar storage systems. A water storage tank system is designed for practical tests for different modes of operation (charging mode, discharging mode, charging & discharging mode simultaneously) in experimental part. The temperature inside the tank is measured experimentally at three different levels. It was shown that the thermal stratification inside the tanks depends differently on the flow rate, the heat losses as well as the initial temperature in the tank. A 3D computational fluid dynamic (CFD) model using the commercial software package CFX 15 was used to simulate the temperature distribution along the tank and to evaluate the stratification number. The model consist from vertical cylindrical tank of high (1.5m) and inlet diameter of (0.55m). The results shown that the heat losses from the storage tank to the ambient is a main ingredient in retrogression of the thermal stratification within un-insulated tank and the best thermal stratification can be obtained for charging mode of operation. A numerical comparison between two cases (insulated and uninsulated wall surface) was carried out and a performance parameter the degree of stratification was calculated for each case. The experimental and numerical results show reasonable agreement. The average deviation between the experimental and numerical degree of stratification are in order of about (4%).

**Keywords: thermal stratification; water storage tank; CFD; heat losses.**

# 1. Introduction

In recent years, the investigation of the thermal stratification in storage tanks has become one of the most important subjects for solar energy systems. In this case many experimental and numerical studies have been carried out by several authors. A thermal stratification of water is formed through the cooling process. The cold water collected at the bottom part while hot water rises to the top of the tank. This condition occurs even if all the water inside the tank is initially at a regular temperature. Before releasing heat from the tank to the ambient, the tank wall will cools a thin perpendicular layer of water along the tank wall. Part of this heat is then transferred by diffusion across the center of the tank. The water of the vertical layer becomes intensive more than its surrounding and then slips towards the bottom of the tank forming the stratification .

Thermal stratification in storage tanks has been the subject of various experimental and numerical studies. **[1], [2], {3]** It have been shown that thermal stratification is influenced by a number of factors such as mixing due to the inlet and outlet streams, heat losses to the surrounding and tank shape.**[4]** was investigated the des stratification during hot water draw-offs in solar tank with different inlets flow rate. They found that mixing during hot water draw-offs decreased the yearly thermal performance of the solar system . **[5],** investigated experimentally the thermal behavior and stratification of hot water storage tanks during the stagnation mode for three different Aspect Ratios (AR) of the tank, namely 0.5, 1 and 2. They found that a better thermal stratification is achieved by increasing the aspect ratio . **[6],** studied numerically the thermal behavior of a vertical and horizontal domestic hot water storage tank during the dynamic mode. They found that the vertical orientation is the efficient design for a stratified storage tank . **[7],** studied and compared two storage tanks with different cold water inlet devices for small Solar Domestic Hot Water, It was shown that the thermal stratification inside the two tanks depends differently on the flow rate, the draw-off volume, as well as the initial temperature in this work, the thermal stratification has been studied experimentally & numerically for four different inlet flow rate to show the effect of heat losses on the stratification degree along the tank.

# 2- Experimental Setup and Procedure

A vertical galvanized steel storage tank with diameter (0.55) m, thickness (0.002) m, length (1.5) m and capacity (270) L was used in this study. There are two ports of diameter 12.7 mm located at each side of the tank for supply & draw-off the water.

The inlet and outlet ports are located at 10 cm lowers than the top and 10 cm upper than the bottom respectively. The charging part of the experimental apparatus consist mainly of water pump in charging cycle and water heating unit while the discharging part consist mainly of water pump in discharging cycle and heat dissipation unit as shown in fig 1.

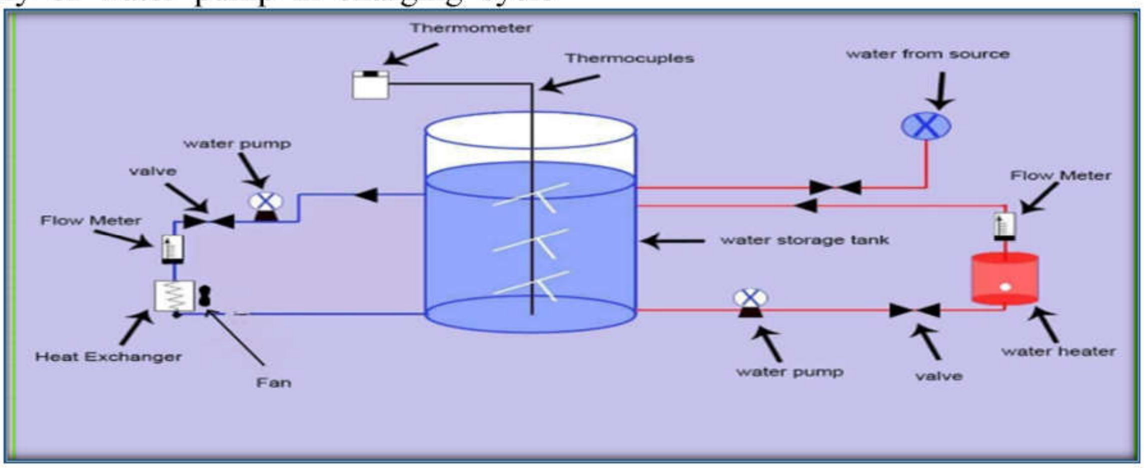



**Fig. 1 schematic diagram of test rig.**

There are nine K-type thermocouples which (three thermocouples at each level) were distributed along the tank with a distance 15, 75, 135 cm respectively from the tank base. These thermocouples are fixed on a stands placed on the centerline of the tank are used for monitoring the temperature distribution of water in the tank as shown in fig (2). Four digital thermocouples were used to measure the temperature of water supply and draw-offs from the tank. Experiments were carried for four different flow rates 4, 6, 8 & 10 L/min during 6 hours operating period for charging mode.

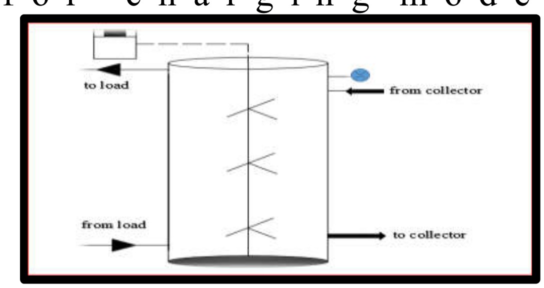



**Fig. 2 Distribution of measuring temperature within the tank.**

The initially water temperature in the tank was nearly at 28C°and the hot water supply was at 50C°.

# 3. Numerical Analysis:

In this present work, the various operating conditions influence on the stratification performance for thermal energy storage tanks are simulated, by using ANSYS Fluent (CFX) . The purpose of this work is to describe precisely the thermal behavior of a vertical hot water storage tank during the dynamic mode of operation . The numerical results obtained are compared with experimental data based on this work . The validated CFD model is then used to explore in detail the influence of the thermal insulation on thermal stratification along the tank during charging mode at flow rate of water (4, 6, 8 & 10) L/min and to comparing the degree of stratification between the experimental and numerical works. The physical model for charging process in cylindrical tank consists of: the flow through the ordinary inlet and outlet ports is at turbulent models (*k*–epsilon model), the inlet hot water is entered from top of the tank and the outlet cold water exit, from the bottom of the tank, the inlet supply has uniform flow rate and temperature . Temperatures of the flows are applied at the inlets only: for the outlets they are computed at the numerical simulations .

**Computational Domain**

In the present work, the system consists of a vertical cylindrical storage tank which is made from galvanized steel sheet with (2mm) thickness. The physical model for charging mode process in cylindrical storage tank is illustrated in figure (3).

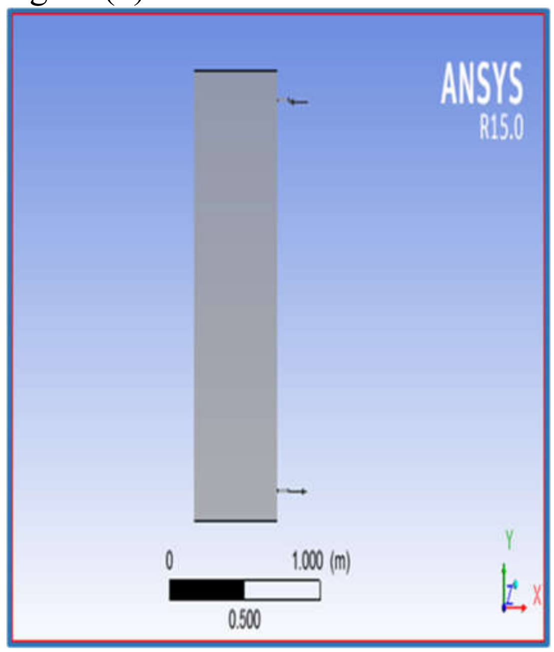



**Fig.3 Geometrical model of the solar water storage tank for charging mode.**

The geometrical model was mainly consisting of:

1- Vertical cylindrical tank of high (1.5m) and inlet diameter of (0.55m).
2- Two flow inlet and outlet ports of inner diameter (1.27cm). The inlet flow port is located at a distance of (10cm) from the top surface of the tank, and the outlet flow port is located at the (10cm) distance from the bottom of the tank.

The inlet hot water is enter from top of the tank and the outlet cold water is exit from the bottom of the tank as shown in Figure 3. The working fluid in the storage tank is water. The flow rate inlet boundary condition is applied to the fluid flow, and the outlet of the water storage tank is assigned to be a pressure outlet boundary condition .

- ***Governing Equations:***

The governing equations of the problem are the continuity equation, the momentum equation and the energy equation .

***1. Continuity Equation***

For an incompressible fluid, the continuity equation for three dimensional flow can be written in cylindrical coordinates as:

$$\left(\frac{\partial\rho}{\partial t}+\frac{1}{r}\frac{\partial(\rho r v_r)}{\partial r}+\frac{1}{r}\frac{\partial(\rho v_\theta)}{\partial\theta}+\frac{\partial(\rho v_z)}{\partial z}\right)=0 \qquad (1)$$

***2. Momentum Equation***

- ***Momentum Equation in the r-direction***

$$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial_r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial\theta}-\frac{v^2{}_\theta}{r}+v_z\frac{\partial v_r}{\partial z}\right)=\mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial r v_r}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial\theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial\theta}+\frac{\partial^2 v_r}{\partial z^2}\right)-\frac{\partial P}{\partial r}+\rho g_r \quad \text{(2-a)}$$

- ***Momentum Equation in the θ-direction***

$$\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)=\mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial r v_\theta}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial\theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial\theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right)-\frac{\partial P}{\partial\theta}+\rho\, g_\theta \quad \text{(2-b)}$$

- ***Momentum Equation in the z-direction***

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial\theta}+v_z\frac{\partial v_z}{\partial z}\right)=\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial\theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right)-\frac{\partial P}{\partial z}+\rho g_z \quad \text{(2-c)}$$

## *3. Energy equation*

For Newtonian fluid at constant thermal conductivity (k) the energy equation can be written as:

$$\rho Cp\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_\theta\frac{1}{r}\frac{\partial T}{\partial\theta}+v_z\frac{\partial T}{\partial z}\right)=k\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial\theta^2}+\frac{\partial^2 T}{\partial z^2}\right)+\mathrm{s} \quad (3)$$

Where (s) is a source term. The governing equations mentioned above are solved taking into account the following assumptions":

1-Turbulent flow, since the Reynolds number corresponding to this study is over 4000, the flow through the storage tank is typically turbulent".

2-Water properties are supposed constant.

3-Boussinesq approximations are adopted in water density modeling, water density is treated as a constant value in all solved equations with the exception of linear density variations in the buoyancy term". $\rho = \rho_0[1-\beta(T - T_0)]$

"In this paper, The results are statistically very low $p$-value (in a range of $0 \leq p$-value $\leq 8\times10^{-7}$). Hence, the $k$–epsilon model is retained for all given simulations turbulence model with full of the transient behavior of thermal stratification .

- **Stratification Number**

The stratification number (Str.) defined by [6] as the ratio of the mean of the transient temperature gradients to the maximum mean temperature gradient for the charging mode, the mathematical formula of this number can be written as:

$$Str. = \frac{\overline{(\partial T/\partial y)_t}}{\overline{(\partial T/\partial y)}_{max}} \quad (4)$$

Where:

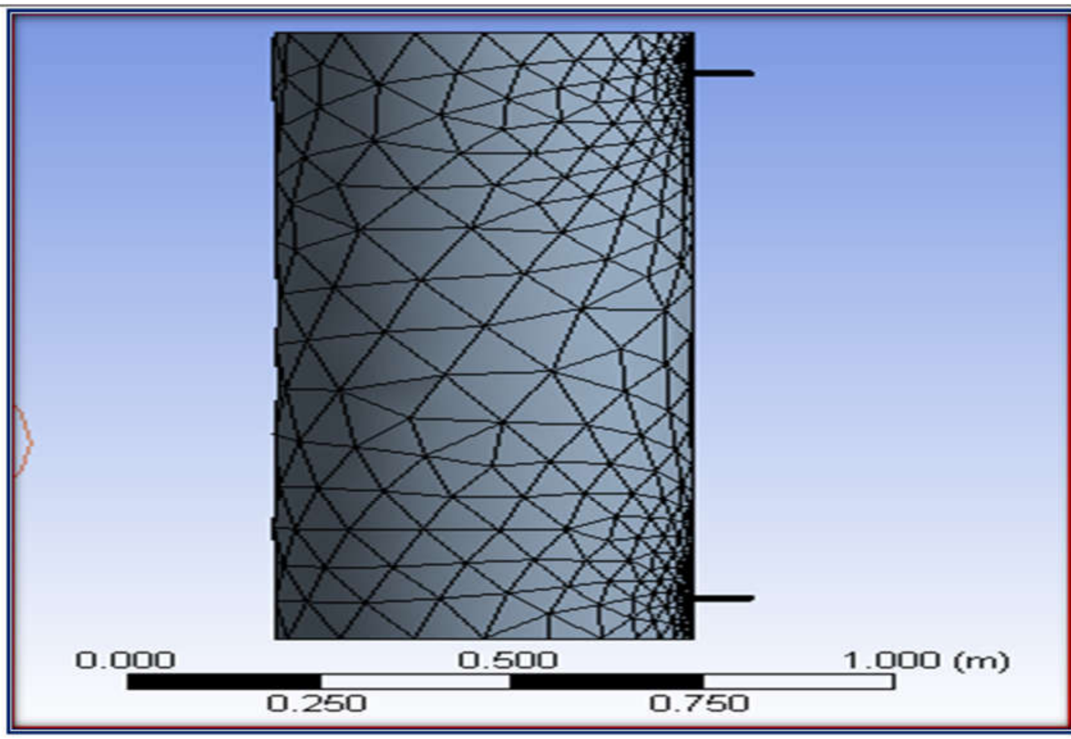
$$(\frac{\overline{\partial T}}{\partial y})_t = \frac{1}{j-1}[\sum_{j=1}^{j-1}(\frac{T_{j+1} - T_j}{\Delta y})] \quad (5)$$

$$(\frac{\overline{\partial T}}{\partial y})_{max} = \frac{T_{max} - T_{in}}{(J-1)\Delta y} \quad (6)$$

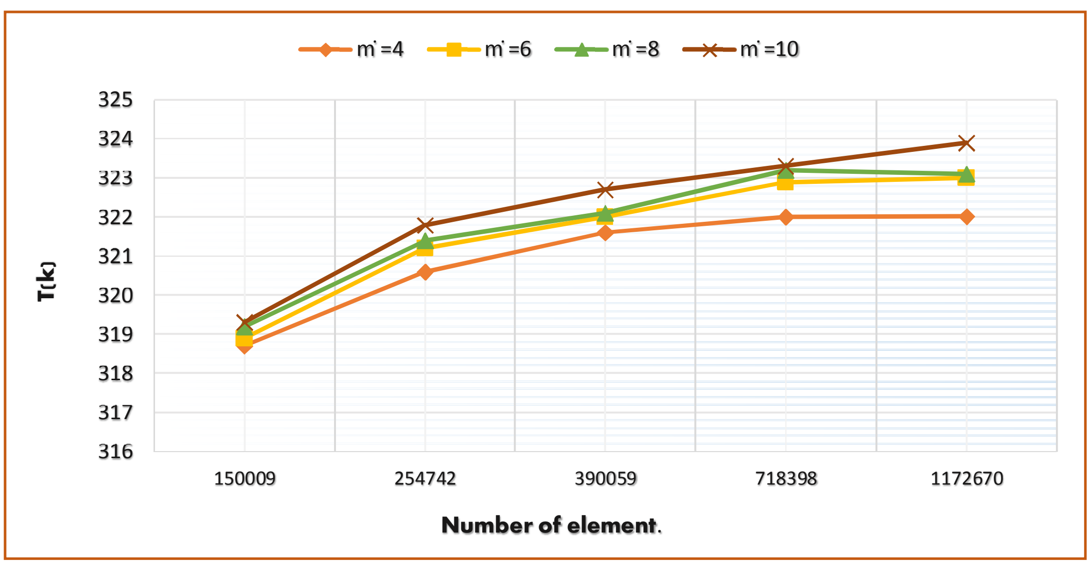
In order to test the validity of this correlation, the experimental stratification number was compared with the numerical one, good agreement was obtained. Equation (4), can be solved by using Microsoft EXCEL (15).

**Mesh Generation**

Mesh generation was accomplished by utilizing of a tool which is named (Mesh) in the Toolbox under the Component Systems menu. The kind of the using mesh is the tetrahedral mesh which consists of triangular elements. This type of mesh is significantly filling all spaces with constant elements size approximately as displayed for demonstration purposes in Figure 4-a.




A- Sample of Tetrahedral mesh for illustration purposes




B- Grid independence.

Fig.4 mesh of cylindrical tank & Grid independence.

This helps to reach the convergence state in short time. The suitable size of mesh element that should be used is estimated by using of grid independence procedure as shown in fig.4-b. The suitable number to mesh element should be equal to (1172670) element.

- **Boundary Condition:**

In the present numerical model it is used the following types of boundary conditions as shown in table.1:

**Table .1 Boundary condition**

| | |
|---|---|
| HEAT FLUX | $q'' = 0$ for insulated wall |
| ADIABATIC CONDITION at the wall | $v_r, v_\Theta, v_z = 0$ *and* $\partial T/\partial r$=0 |
| OUTSIDE TEMP. | Ambient temperature = 300 K.<br>For uninsulated wall, The convective heat transfer coefficient is calculated based on the work of [8] |
| SLIP CONNDITION | NO SLIP |
| WATER INLET TEMP. | 333 K |
| MASS FLOWRATE | $\dot{m}$=0.06 kg/s, $\dot{m}$=0.1 kg/s, $\dot{m}$=0.13 kg/s and $\dot{m}$=0.15 kg/s |
| INITIAL CONDITION | The pressure in the tank is 1 atm.<br>The initial velocity of the water in the tank is assumed zero. |

## 4. Results and Discussions:

### 4.1 Experimental Results

- **The Stratification in the Storage Tank without Thermal Insulation.**

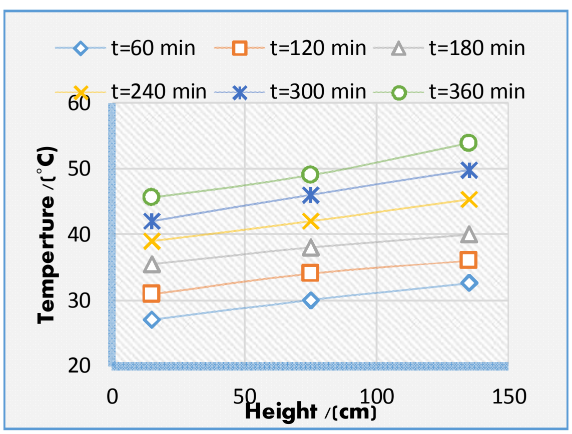
Fig (5-a), (5-b), (5-c) and (5-d) shows the temperature distribution of water at different levels (15, 75 and 135) cm along the storage tank and at different flow rates (4, 6, 8 and 10) L/min respectively for each hour during an experimental period of operation equal to 6 hours. In fig (5-a), the flow rate of water equal to 4L/min, the temperature of water in the tank was at a uniform temperature about (25˚C) at the beginning of the test. the temperature of water at different levels along the tank show a little difference during the early hours of the test and then the difference will increase with time until reach its maximum value (9 ˚C) in the last hour of operation where the value of the degree of stratification is (0.46). In figs (5-b), (5-c) and (5-d), the temperature of water in the tank is 30˚C at the beginning of the test, the behavior of water temperature difference within the tank is shown similar to that of fig (5-a). The thermal stratification, beginning at small value, and then increases with time until reach its maximum value in the last hour of the test. The values of the stratification degrees for the flow rates (6, 8 and 10) l/min are (0.39, 0.38 and 0.35) respectively. The results in this part of study show that the thermal stratification was at lowest value due to thermal losses from the tank to the surroundings. In addition, it was decreased and destroyed with increasing water flow rates because increasing the mixing effects between the inlet hot water and the water in the storage tank.

- ***The Stratification in the Storage Tank with Thermal Insulation.***

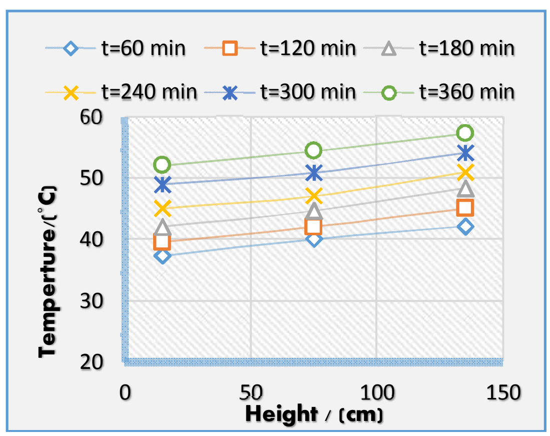
Fig (6-a), (6-b), (6-c) and (6-d) show the effect of thermal insulation on the temperature of the water at different levels in the storage tank and at different flow rate (4, 6, 8 and 10) L/min respectively during operation period. The temperature of the water in the storage tank is about (30˚C) at the beginning of test. Fig (6-a) illustrates that the stratification increased at low flow rate (4L/min) with time until reach its maximum value at last hour of operation. At this hour the degree of stratification is (0.66). When the flow rate increases, the stratification decreased due to mixing as shown in fig (6-b), (6-c) and (6-d) and the degree of stratification during the last hour of operation at 6 L/min is (0.61), at 8 L/min is (0.52) and at (10) L/min is (0.5) respectively. When using the thermal insulation, the results for this mode of operation (charging mode) illustrates an improve in thermal stratification and the heat would be maintained more time inside the tank in comparison with the same mode of operation without using thermal insulation.

**4.2 Numerical Results**

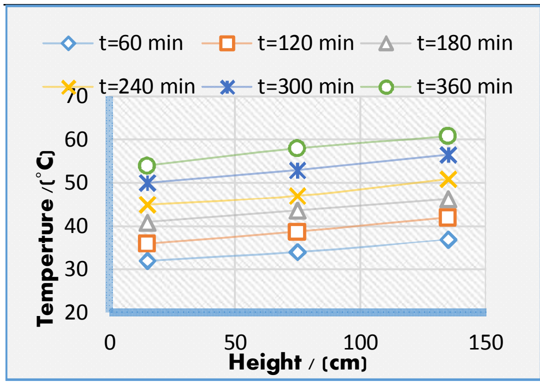
Figures (7), (8), (9) and (10) show the temperature distribution of water along the storage tank without thermal insulation on the external surface at different flow rate (4, 6, 8 and 10) L/min respectively during operating period of 6 hours. The temperature of water in the storage tank in the beginning of calculation process is assumed uniform (30˚C) and the inlet hot water is (60˚C). The degree of stratification at flow rate (4, 6, 8 and 10) L/min are (0.52, 0.45, 0.32 and 0.27) respectively. The thermal stratification in the tank is clear at flow rate 4 L/min as shown in fig (7). When the flow rate increase, the heat losses & mixing effects were increase in which leads to destroy the thermal stratification within the water storage tank as shown in fig (8), (9) and (10).Figures (11), (12), (13) and (14) show the temperature distribution in the water storage tank with thermal insulation on the external surface at different flow rate (4, 6, 8 and 10) L/min respectively during operating period of 6 hours. The temperature of water in the storage tank at the beginning of test is 30˚C and inlet hot water is assumed constant 60˚C. The degree of stratification for flow rate (4, 6, 8 and 10) L/min are (0.72, 0.64, 0.6 and 0.53) respectively. The thermal stratification is clear and increase with time at 4 L/min flow rate when the external walls at adiabatic condition as shown in the fig (11) due to decrease heat losses from the storage tank to the environment. Fig (12) shows the temperature distribution at flow rate 6 L/min, the mixing increase and destroyed the stratification. Figures (13) and (14) show that, the influence of high flow rate is clear in the storage tank and the mixing effects destroyed the stratification.



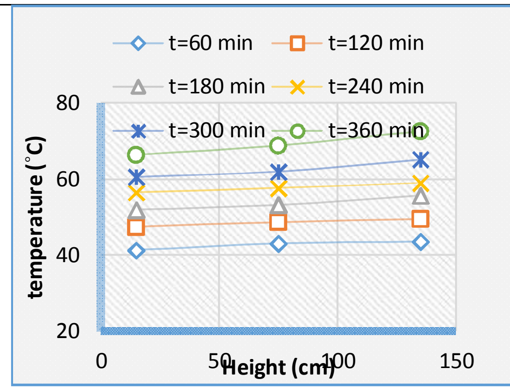

**(a) Water flow rate 4 l/min.**




**(b) Water flow rate 6 l/min.**

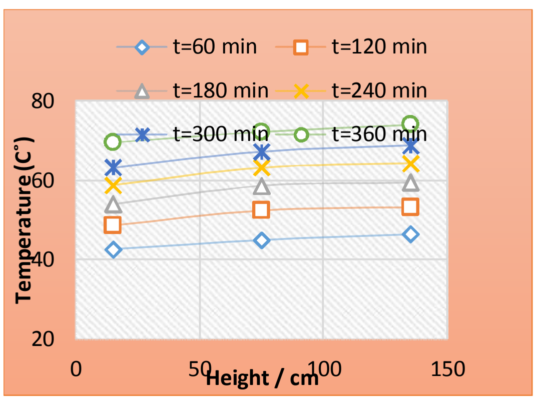



(c) Water flow rate 8 l/min.

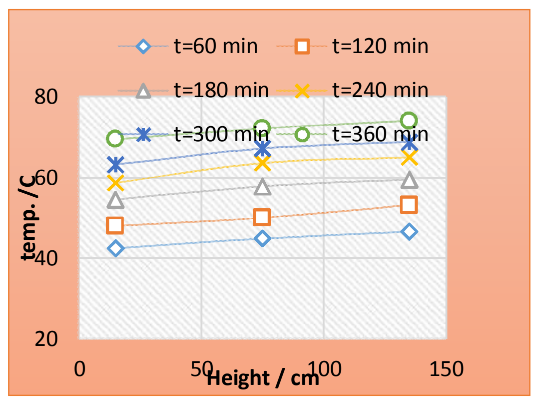



(d) Water flow rate 10 l/min.

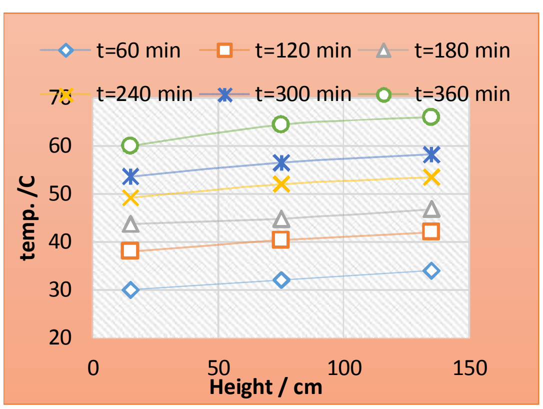
**Fig.5 Hourly temperature distribution of water within uninsulated tank for charging mode.**



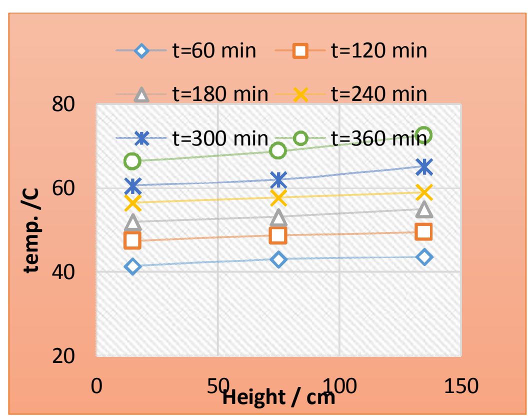

(a) Water flow rate 4 l/min.




(b) Water flow rate 6 l/min.




(c) Water flow rate 8 l/min.




(d) Water flow rate 10 l/min.

**Fig.6 Hourly temperature distribution of water within insulated tank for charging mode.**

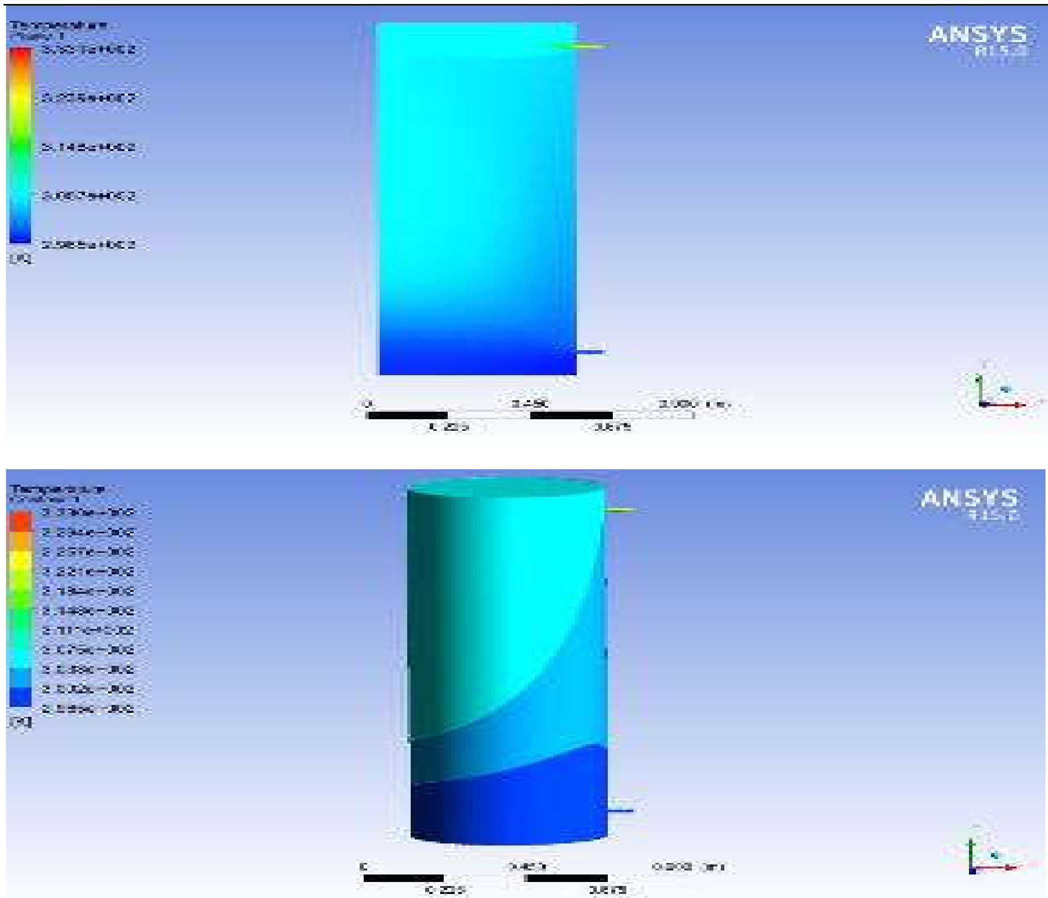
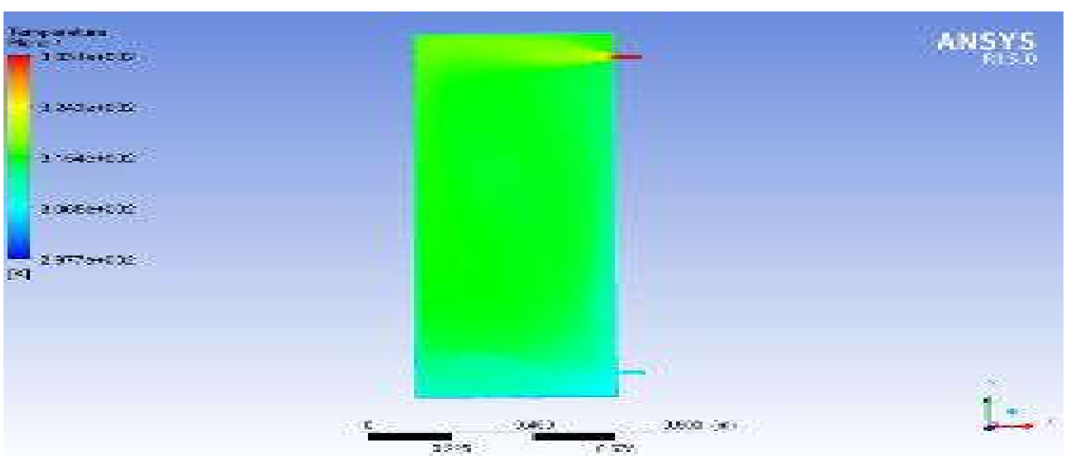



**Fig.7 2-D & 3-D Temperature distribution of water along uninsulated tank at 4L/min for charging mode.**



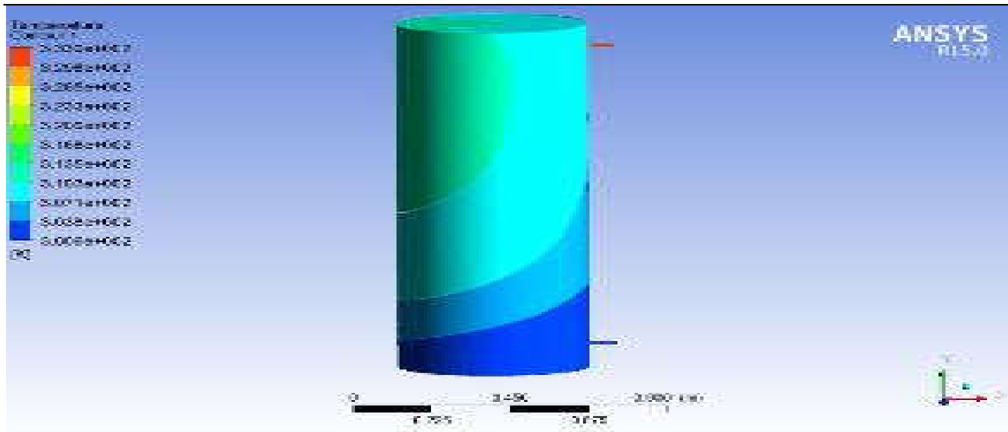



**Fig. 8 2-D & 3-D Temperature distribution of water along uninsulated tank at 6 L/min for charging mode.**

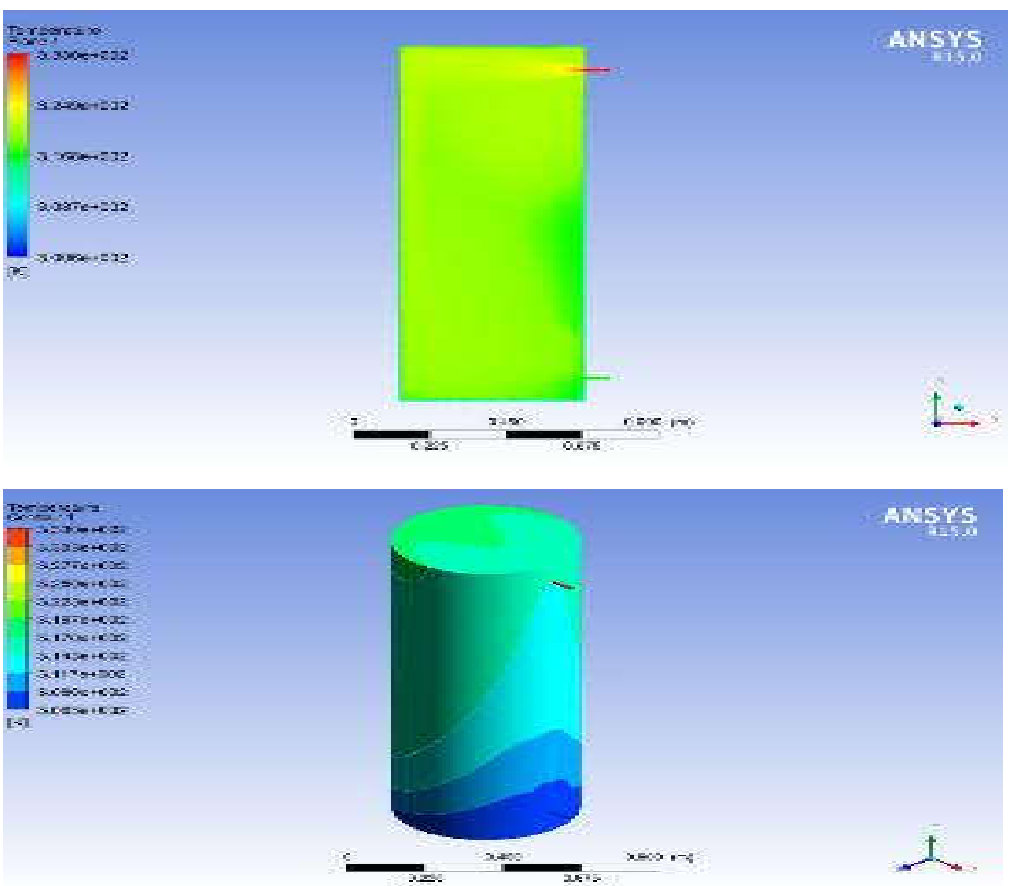



**Fig.9 2-D & 3-D Temperature distribution of water along uninsulated tank at 8 L/min for charging mode.**

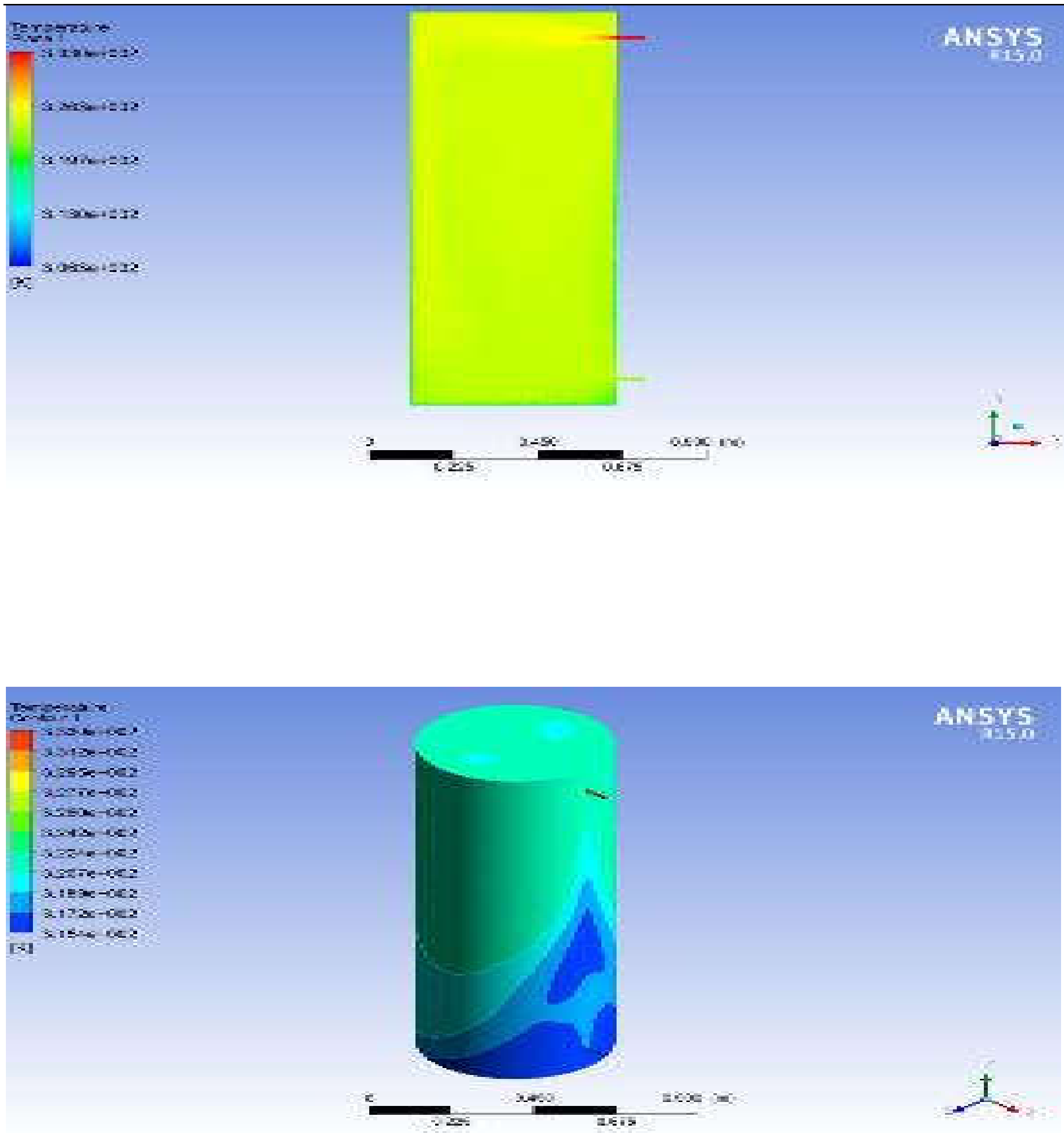



**Fig.10 2-D & 3-D Temperature distribution of water along uninsulated tank at 10 L/min for charging mode.**

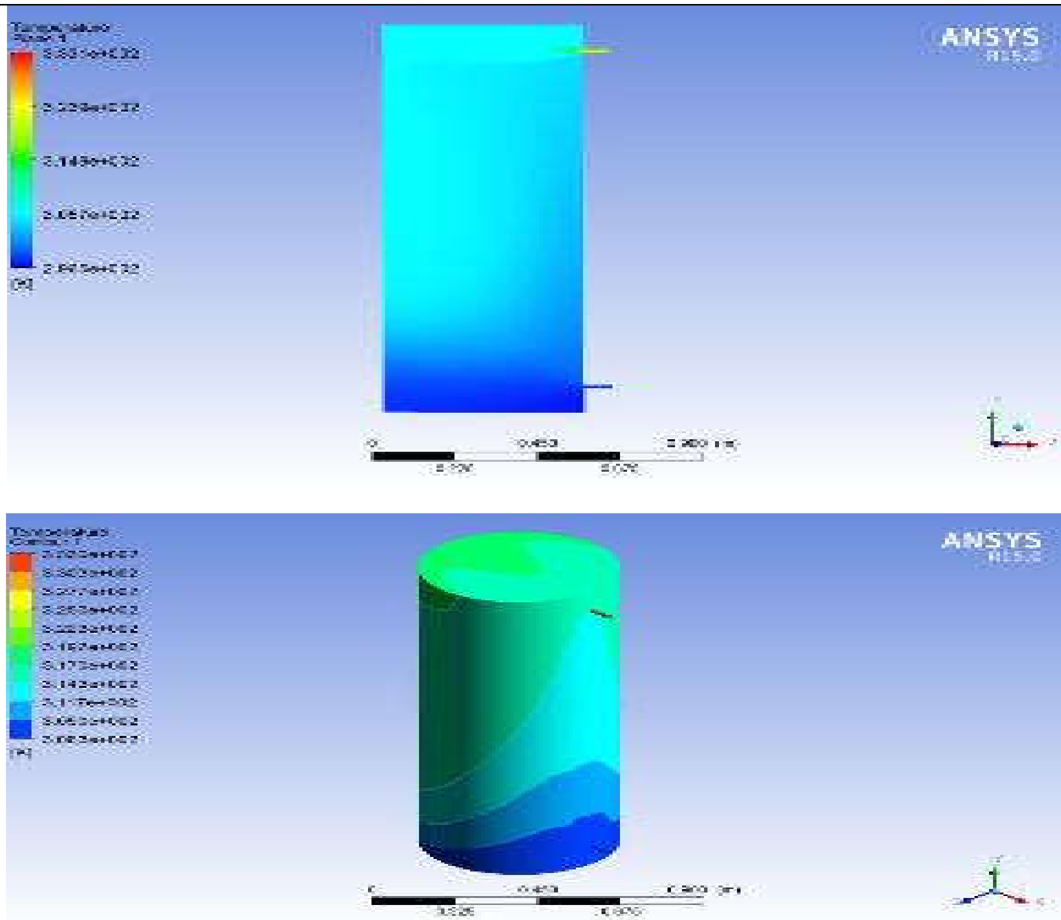
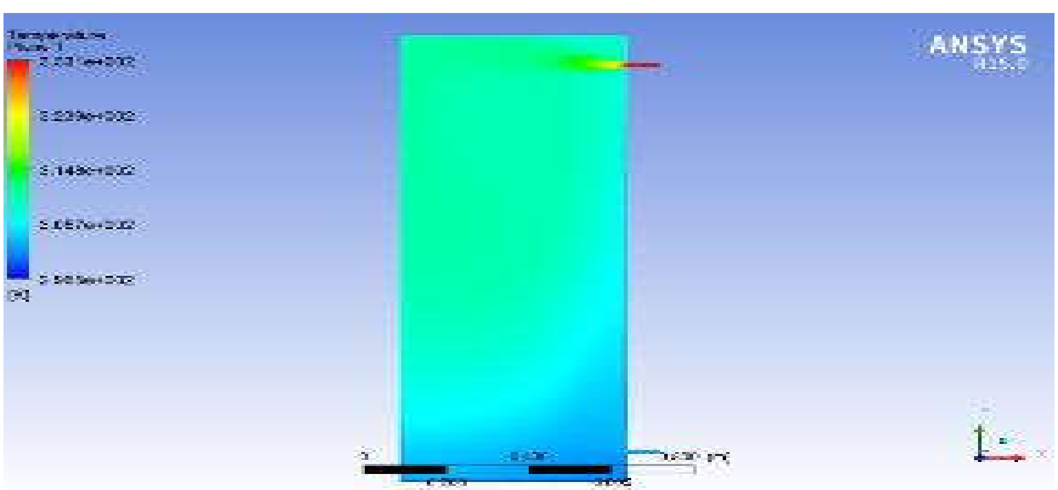



**Fig.11 2-D & 3-D Temperature distribution of water along insulated tank at 4L/min for charging mode.**



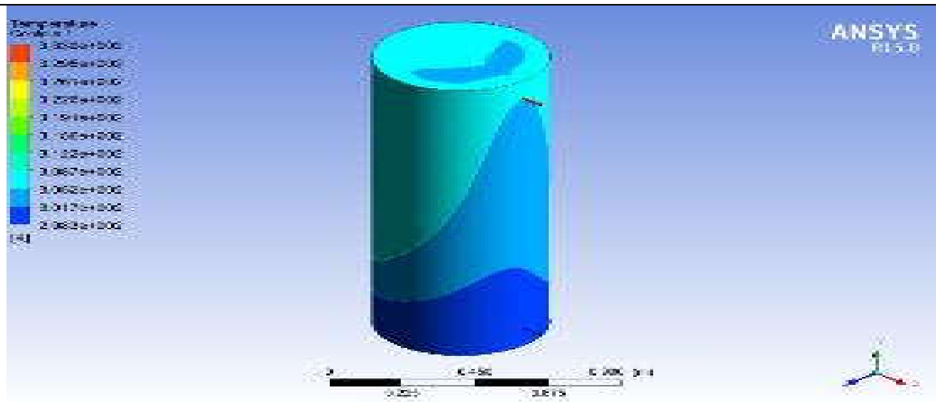



**Fig. 12 2-D & 3-D Temperature distribution of water along insulated tank at 6 L/min for charging mode.**

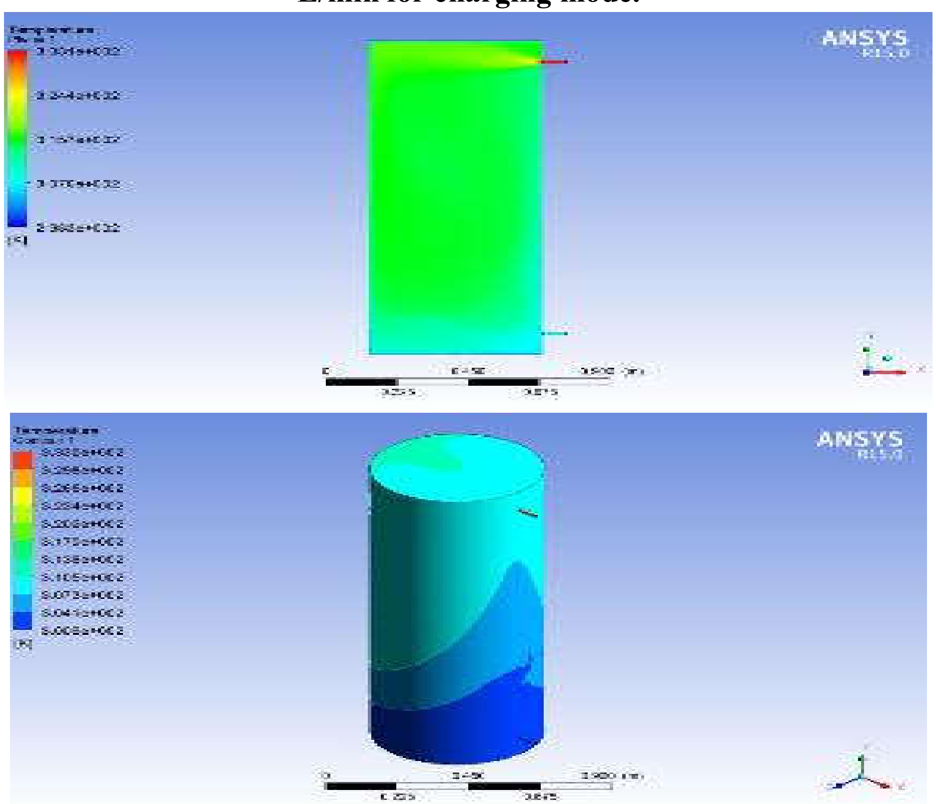



**Fig. 13 2-D & 3-D Temperature distribution of water along insulated tank at 8 L/min for charging mode.**

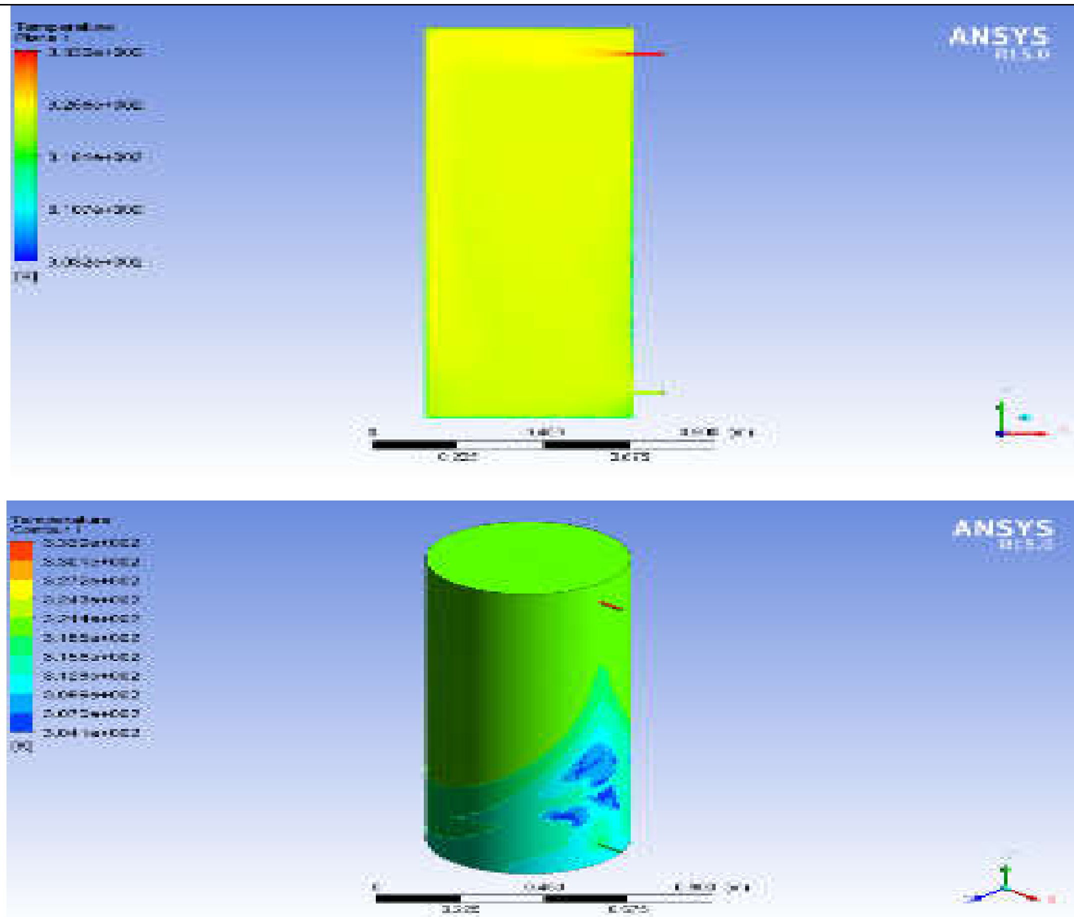



**Fig. 14 2-D & 3-D Temperature distribution of water along insulated tank at 10 L/min for charging mode.**

## *5- CONCLUSIONS:*

In this study, the thermal behavior of domestic hot water storage tanks for the dynamic mode has been examined experimentally and numerically . From the obtained result, the below conclusions can be drawn:

1. It has been observed from studying the effect of water flow rate that the degradation of thermal stratification increases with the increase of flow rates a cause of mixing effect.
2. The heat losses from the storage tank to the ambient is a major factor in degradation of the thermal stratification in an un-insulated tank.
3. The best thermal stratification can be obtained for charging mode at lower flow rate.
4. The stratification number of uninsulated tank is considerably lower than the insulted tank.

## Nomencluter

| | |
|---|---|
| j: Number of water layers. | $\dot{m}$: Mass flow rate, Kg/s. |
| P: pressure, $N/m^2$. | r,Θ,z: Cylindrical coordinates. |
| s: source term | Str.: Stratification number. |
| t: time , s. | Tenv: Temperature of environment, K |
| Tj: Temperature of the j-th layer, K. | Tj: Temperature of the j-th layer, K. |
| Tin: Inlet temperature of the hot water, K. | Tmax: Maximum temperature, K. |
| $v_r, v_\Theta, v_z$: velocity components, m/s. | β: coefficient of thermal expansion, $K^{-1}$ . |
| ρ: Density $Kg/m^3$. | ρo: Density at operating temperature, $Kg/m^3$. |
| Δy: Layer thickness, m. | |

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# دراسة تأثير فقدان الحرارة على التقسيم الحراري في خزان الماء الساخن الأسطواني

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الخلاصة:

يتم دراسة خزان مع مختلف معدل تدفق مدخل الماء الساخن (4 و 6 و 8 و 10) لتر/دقيقة للجدار المعزول و غير المعزول عمليا ونظريا.

الهدف من الدراسة هو إظهار تأثير الخسائر الحرارية من الخزان إلى المحيط على التطبق الحراري داخل خزانات المياه، وتقييم إمكانية تعزيز في الأداء الحراري لأنظمة التخزين الشمسية. تم تصميم نظام خزان المياه للاختبارات العملية لأوضاع مختلفة من العملية (وضع الشحن، وضع التفريغ، شحن وتفريغ الوضع في وقت واحد). يتم قياس درجة الحرارة داخل الخزان تجريبيا على ثلاثة مستويات مختلفة. وقد تبين أن التقسيم الحراري داخل الخزانات يعتمد بشكل مختلف على معدل التدفق، وخسائر الحرارة وكذلك درجة الحرارة الأولية في الخزان. تم استخدام نموذج ديناميكي للسوائل الحسابية ثلاثية الأبعاد (CFD) باستخدام حزمة البرامج التجارية CFX.15 لمحاكاة توزيع درجة الحرارة على طول الخزان ولتقييم عدد الطبقات. تم التحقق من صحة النموذج المقترح مع البيانات التجريبية التي تم الحصول عليها من هذه الدراسة. وقد استخدمت نتائج المحاكاة لتحليل الخسائر الحرارية، وخصائص التدفق، والتطور الطبقي الحراري أثناء وضع الشحن. وأجريت مقارنة عددية بين حالتين (سطح معزول وغير معزول) وتم حساب معامل أداء درجة التطبق الطبقي لكل حالة

**الكلمات المفتاحية: التطبيق الحراري، خزان الماء ,الخسائر الحرارية**