Modeling of Transient Stratification in Cold Water Storage Tanks

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Abstract

Thermal stratification in liquid tanks is rapidly destroyed with time because of the forced and the free convection between liquid layers along the tank height. Therefore, the aim of the present work is to enhance thermal stratification in cold water storage tanks during both charging and standby modes by fitting perforated obstacles (P.O.) inside the tank with various numbers, materials, opening area percentages (O.A.P); and with different opening area arrangements. Three-dimensional numerical analysis by (ANSYS 14.0) package with (Flotran Fluid element 142/3D) has been used to simulate the heat transfer inside the storage. The numerical investigation for various number of perforated obstacles of 4, 6 and 8 with both inline and staggered arrangement have been tested. The effect of O.A.P (from 3.14 to 44%) on thermal stratification has been investigated. The initial runs of the numerical investigation have been used for designing the experimental test rig. The experimental work included testing various perforated obstacles materials of Aluminum sheets, Aluminum composite panels and Fiber-glass/polyester Composite material (F./P. Comp.) with different O.A.P. and opening area arrangements (inline and staggered). A detailed comparison between numerical and experimental results showed good agreement with maximum deviation of about ±12.28. The results indicated that thermal stratification increases with decreasing Reynolds number and O.A.P. The number and location of holes in obstacle is found to have inconsiderable effect compared to O.A.P magnitude. The optimum O.A.P. is found to be between (7% to 16%). Using inline P.O. arrangement shows better enhancement for thermal stratification than staggered arrangement. According to the results obtained from both numerical and experimental work, the optimum thermal stratification has been found to achieve for tank fitted with (8), inline, (F/P. Comp.) material P.O., with 12%O.A.P.

Key words: **: thermal stratification, perforated obstacles, cold water tank, ANSYS.**

1-Introduction

Cold-water storage is used to reduce utility bills and capital investment in air-conditioning system. The efficiency of systems employing sensible thermal storage in water depends largely on maintaining the separation of the warmer and colder water in the tank throughout the operating cycle. Forced and free convection during dynamic mode and free convection during static mode play a major role in thermal energy storage system, where the overall performance is significantly affected by the temperature gradient inside the tank. Thermal stratification in thermal storage tanks is an important parameter in several industrial processes, such as food production and medical applications.

Cold water systems can help balance energy demand and supply by accumulating energy when production exceeds demand and to make it available at a later time for heating and cooling applications and power generation [6]. So, chilled storage tank serves effectively as standby source for cooling in case of power outage that leads to reduce costs. Chilled-water storage was estimated to account for 34% of the total capacity of all cool storage systems in the United States [1]. Most of these systems used naturally stratified storage tank.

Different studies investigated many factors that have an influence on thermal stratification such that, aspect ratio, insulation thickness [12], [3] and volume flow rate of the inlet fluid [8] and enhancement of thermal stratification by various kinds of inlet and outlet diffusers. Zurigat et al, [15] tested theoretically one dimensional flow model and experimentally a cylindrical tank for three types of inlet diffusers. These include solid diffuser, perforated diffuser and perforated diffuser with solid center. The results concluded that perforated diffuser consistently had the best performance. Amy and William [1] studied theoretically temperature profiles in chilled-water storage tank, with upper and lower radial parallel plate diffusers. They concluded that the upper diffuser produced thicker thermoclines during discharge cycles than did the lower diffuser during charge cycles. Mi-Soo et. al. [9], studied numerically and experimentally the mixing characteristics of stratified storage tank with upper and lower diffusers for hot and cold water flow lines. Two types of diffusers are tested, (flat and curved). The results indicated that the performance of the curved diffuser shows better than flat one at low flow rate. Hegazy [4] studied the effect of the inlet designs on the performance of the hot water storage tank experimentally and the mixing degree that produced by three different side-inlets geometry (wedged, perforated and slotted pipe-inlets). The slotted inlet is found to be more efficient and the performance difference between them is more obvious for high flow rate. Lana et. al. [7] used a numerical technique to increase thermal stratification by the mantle tank system that makes use of injection of the collector fluid into the mantle at different levels. It is found that when the collector fluid is injected into the mantle at a proper level according to its temperature, best tank stratification could be achieved. Nedect et. al. [11] analyzed numerically the effect of using different types of a single obstacle on thermal stratification in a cylindrical hot water tank. The results indicate that the obstacle types having gap in the center appear to have better thermal stratification than those having gap near the tank wall.

The main objective of the present work is to enhance transient thermal stratification inside cold water storage tank during both charging and standby modes by utilizing perforated obstacles inside the storage tank with various materials, number, and with different opening area percentages and opening area arrangements.

Numerical Simulation and Theoretical Analysis

□ Transient conservation energy continuity and momentum equations that are shown below and solved using (ANSYS 14.0) package with 3D FLOTRAN software to simulate the liquid tank with and without perforated obstacles of different opening area percentages, pattern arrangements and various numbers [4]. (3-D FLOTRAN ELEMENT 142) model is used to simulate transient flow through perforated plates that involve fluid and/or non-fluid regions. The conservation equations of viscous fluid flow and energy are solved in the fluid regions, while only the energy equation is solved in the non-fluid regions. The model consists of storage tank with a height of 1m and square cross section of the base (40× 40) cm as shown in the physical representation of Figure (1). The tank has two uniform portions, first is the lower inlet portion and second is the upper outlet portion. The storage tank contains different number of the perforated obstacles. After creating the geometry, ANSYS mesh generation tool is used to generate the mesh for the model. Since it is three dimensional model, quadrilateral mesh elements have been used. The ranges of element numbers have been selected between (1352341-2230165) elements [13].

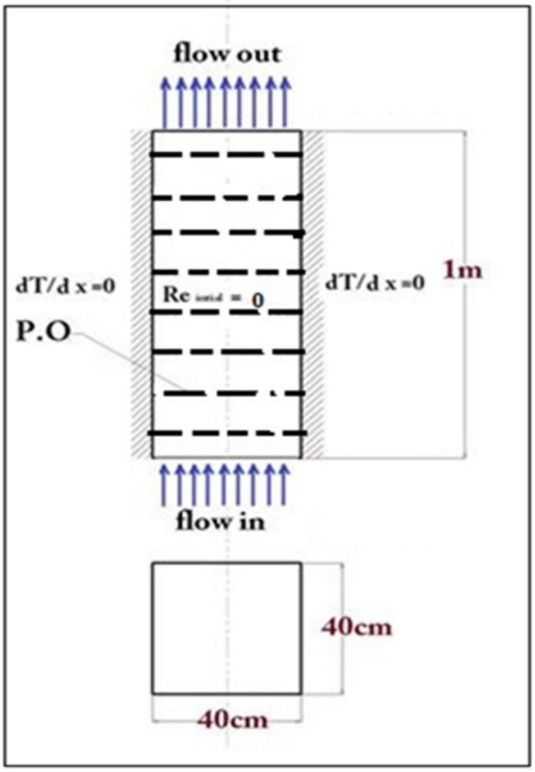


Figure (1): physical representation for numerical simulation

1- Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \textbf{... (1)}$$

2- Momentum equations:

X-Component

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho\, g_x \ldots \quad \textbf{(2)}$$

Y-Component

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho\, g_y \quad \textbf{... (3)}$$

Z-Component

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho\, g_z \quad \textbf{... (4)}$$

3- Energy equation:

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)\ldots \quad (5)$$

Theoretical Analysis

In this work, two stratification indexes for promoting stratification will be calculated. These include:

1- Stratification coefficient

Stratification coefficient is defined as an index for the degree of stratification that based on a mean square deviation of temperatures in the storage from the mean storage temperature (Wu and Bannerot, 1987).

$$\text{Stratification coefficient (Sc)} = \frac{1}{m_{store}}\sum_i m_i\left[T_i - T_{avg}\right]^2 \quad (6).$$

2- Stratification number

The stratification number was found to describe correctly the thermal stratification (Eduard et al, 2013), which is defined as the ratio of the mean of the temperature gradients at any time interval to the maximum mean temperature gradient for the charging/ discharging process [2] It is expressed in the following form

$$Strtification\ number(Sn = \frac{\left(\frac{\partial T}{\partial y}\right)t}{\left(\frac{\partial T}{\partial y}\right)max} \quad (7)\ldots$$

where

$$\left(\frac{\partial T}{\partial y}\right)t = \frac{1}{n-1}\left[\sum_{i=1}^{n-1}\left(\frac{Ti+1-Ti}{\Delta h}\right)\right] \quad (8)$$

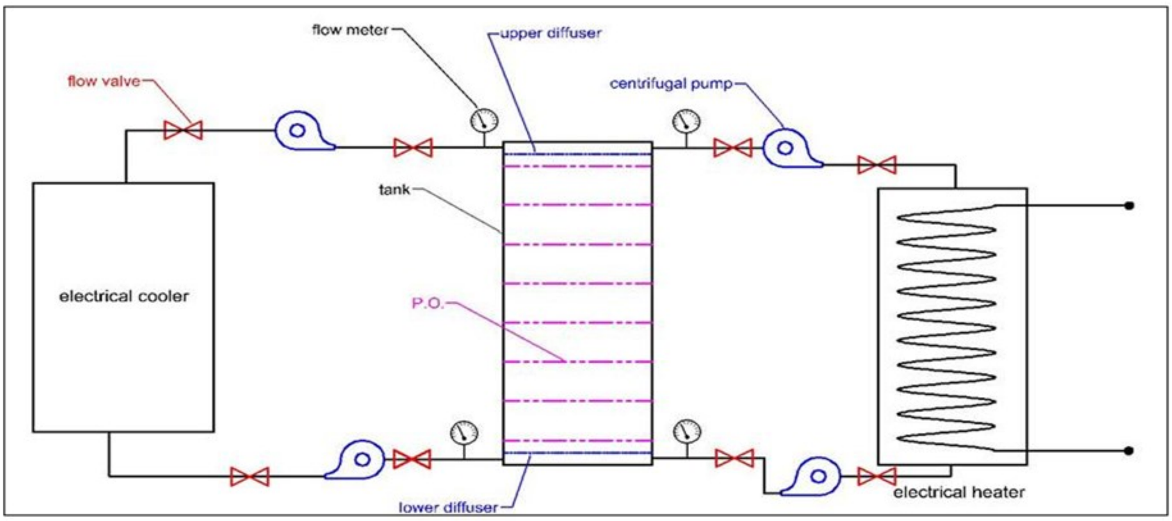
And

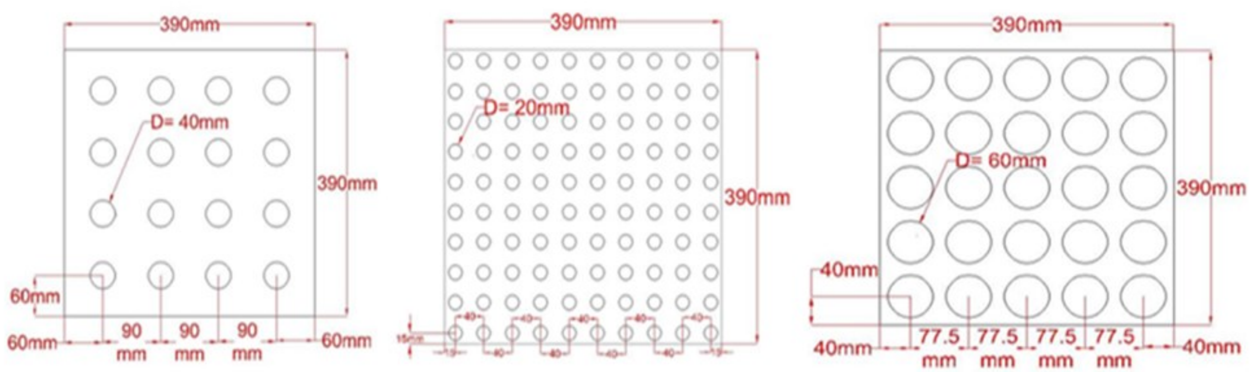
$$\left(\frac{\partial T}{\partial y}\right)max = \frac{Tmax-Tin}{(n-1)\Delta h} \quad (9)$$

2-Experimental work

A well-insulated storage tank fitted with perforated obstacles, as well as, heating and cooling elements are designed, fabricated and installed. The schematic diagram of the test rig with samples of perforated obstacles are shown in **Figure(2)** .The storage tank is made of galvanic steel, with a height of 1m and square cross section of the base (40 cm 40 cm .(

The perforated obstacles (P.O.) that mounted inside the storage tank have high flexibility to enter and getting out the storage tank easily. Both of the P.O. opening area arrangements (inline and staggered) are illustratein figure (3) with samples of various O.A.P.





(a):O.A.P. =12% **(b):O.A.P.=20%** **(c): O.A.P. =44%**

Figure (2): Schematic diagram of test rig with samples of various P.O

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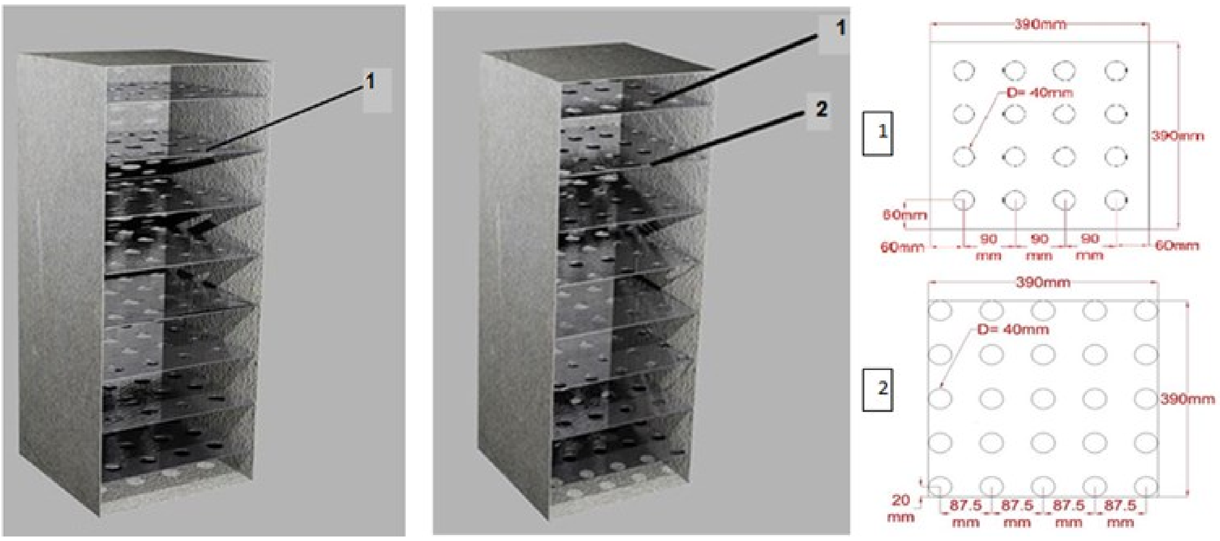


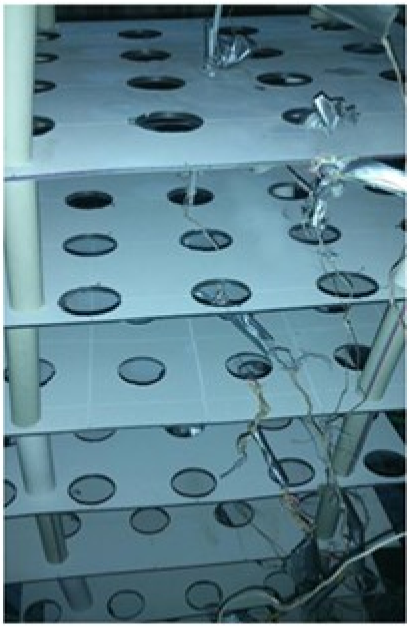
(a) (b)

Figure (3): Opening area arrangement (a) Inline arrangement (b) Staggered arrangement, (1) Sample of 12% O.A.P, (2) Sample of 20 % O.A.P☐

Obstacles material:

Three types of materials are used to fabricate the perforated obstacles; Aluminum sheets, Aluminum composite panels, and fiber glass/polyester composite material (F /P Comp.), as shown in figure (4).The thickness of the Aluminum composite panels is of (4mm) and composed of thermoplastic material sandwiched between two sheets of Aluminum of (0.5mm) thickness with a protective coating on the skin.

In the present work, Fiberglass with weight fraction of 40.2% (the ratio between the weight of fiber to total weight of composite material) has been manufactured. Glass fiber is used as reinforcement because it has low thermal conductivity. It is mixed with polyester resin which is used as a matrix material. Hand lay-up technique was used in this work to prepare the specimens as shown in **Figure(5).** The mold was made of glass and consists of three parts: base, removable barrier, and cover with dimensions of (40 cm ⨯ 40 cm) with a thickness is (4 mm). The inner face of the mold was cleaned and smeared with wax to ensure non adhesion the specimen with mold walls. The hardener with polyester resin was mixed by (2%) of the polyester resin and the mixture is poured to the mold and then the reinforcement layer was applied according to the desired volume fraction. After molding, the cover is used to apply pressure equally all over the sample to eliminate any air gap trapped in the samples. Finally, each specimen is perforated by a drilling machine with the desired O.A.P. A total of 19 thermocouples of type –K were distributed inside tank as shown in **Figure(6)** to record the temperature distribution


a): Aluminum sheet (b): Aluminum composite panels (c):(F/P comp.) material

Figure (4): Various material used for fabricating perforated obstacles

Figure (5): Manufacture of (F/P comp.) material using hand lay-up method

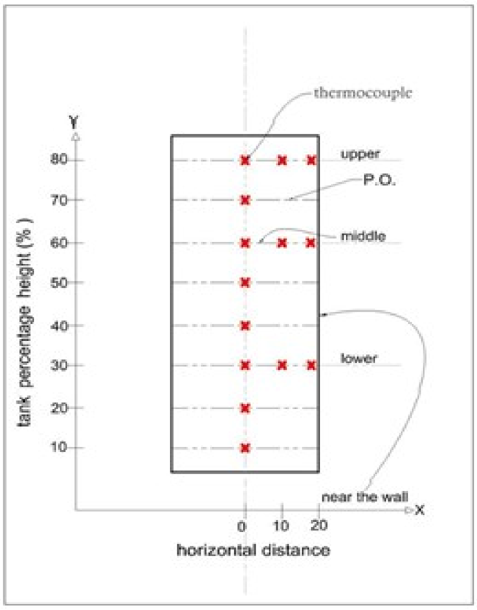


Figure (6): Schematic diagram of Thermocouples positions inside the tank

All experiments were performed at least twice (on different days), to check the repeatability of the data, which was proved to be good. Because the data demonstrated repeatability, only results one of the tests will be presented here. The uncertainties for important parameters and measurements made during the current research have been carried out on the basis of the method proposed by (Moffat, 1985). The maximum uncertainties are ±1.64% for water Reynolds number and ±0.83% for fluid temperatures.

3- Results and discussion

Figures(7)and**(8)** show comparison between numerical and experimental temperature profiles along tank during charging and standby modes respectively; while **Figure(9)** shows the comparison results along transversal direction of the tank.

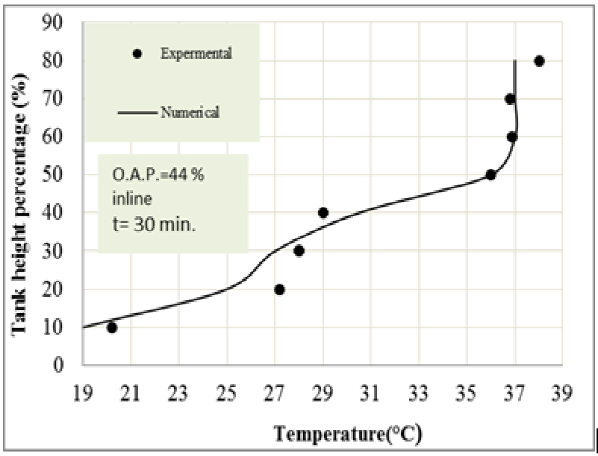


Figure (7): Comparison between experimental and numerical results of AL. P.O. during charging mode

The results indicate that the numerical results have good agreement with the experimental observation. The maximum deviation along the tank height is found to be 9.37% during charging mode and 12.28% during standby mode, while the deviation is found to be 4.5% and 5% for charging and standby modes respectively along the transversal direction.

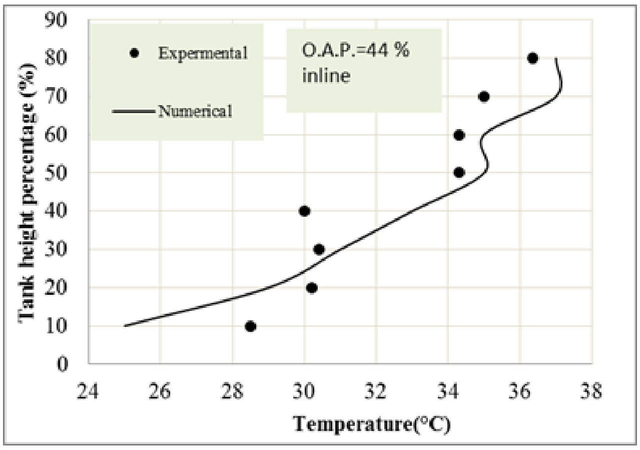


Figure (8): Comparison between experimental and numerical results of AL. P.O. during standby mode

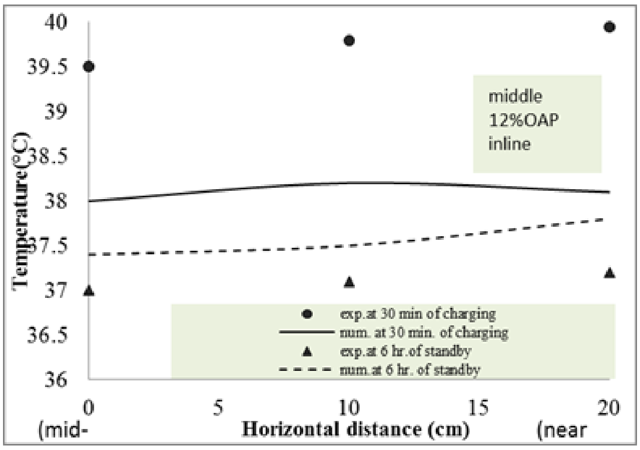
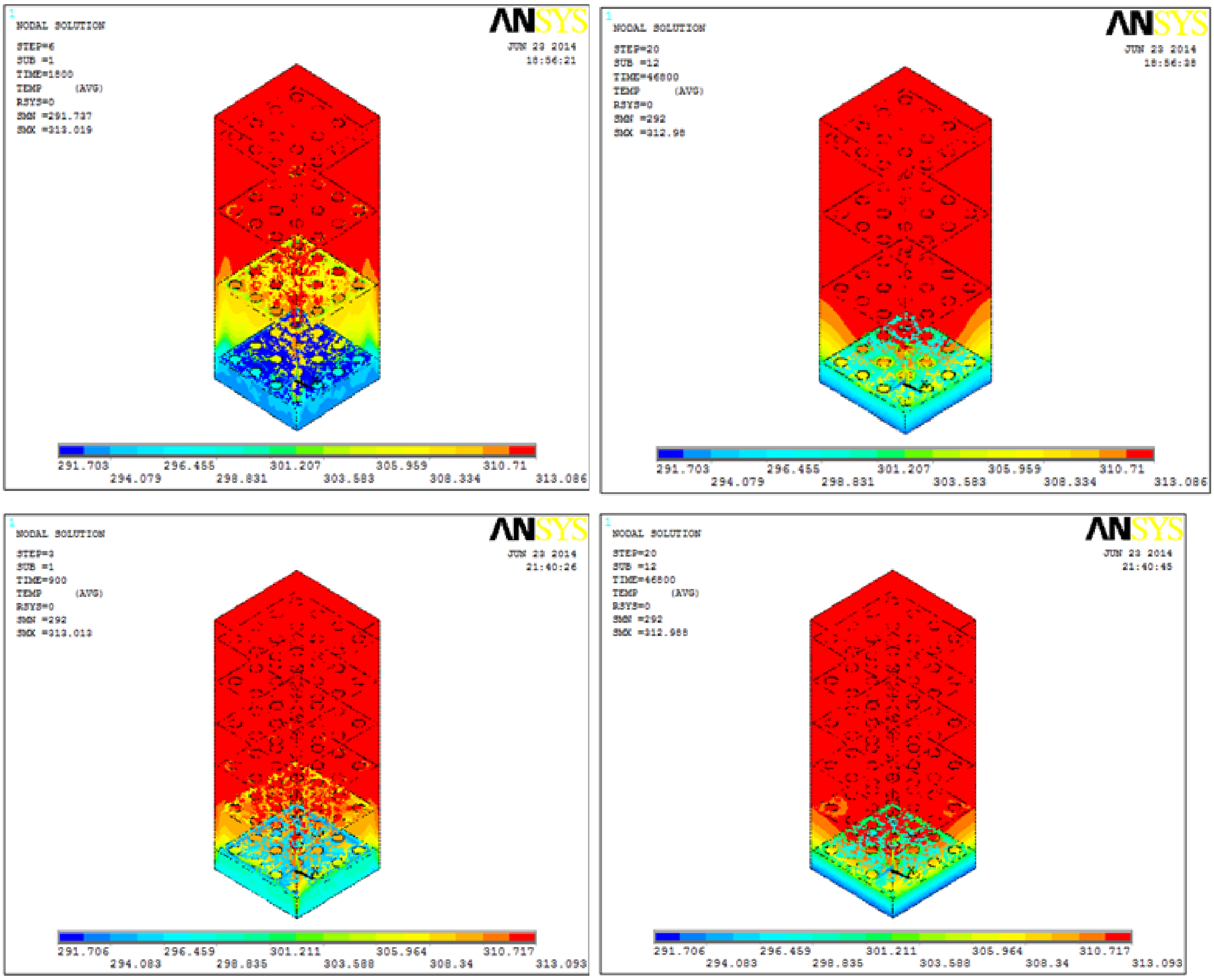


Figure (9): Comparison between experimental and numerical results for temperature profiles along transversal direction

Figure(10) shows transient temperature contours for both charging and standby modes with tank fitted with (4, 6 and 8) perforated obstacles of inline 16% O.A.P. The temperature contours illustrate that thermal stratification is found to increase with perforated obstacles number and the optimum number of P.O. is 8. **Figure(11)** shows the effect of staggered perforated obstacles number for same O.A.P of 16%. These contours indicated that chilled water tank fitted with (6) staggered obstacles shows better performance than tanks fitted with (4) and (8) staggered obstacles



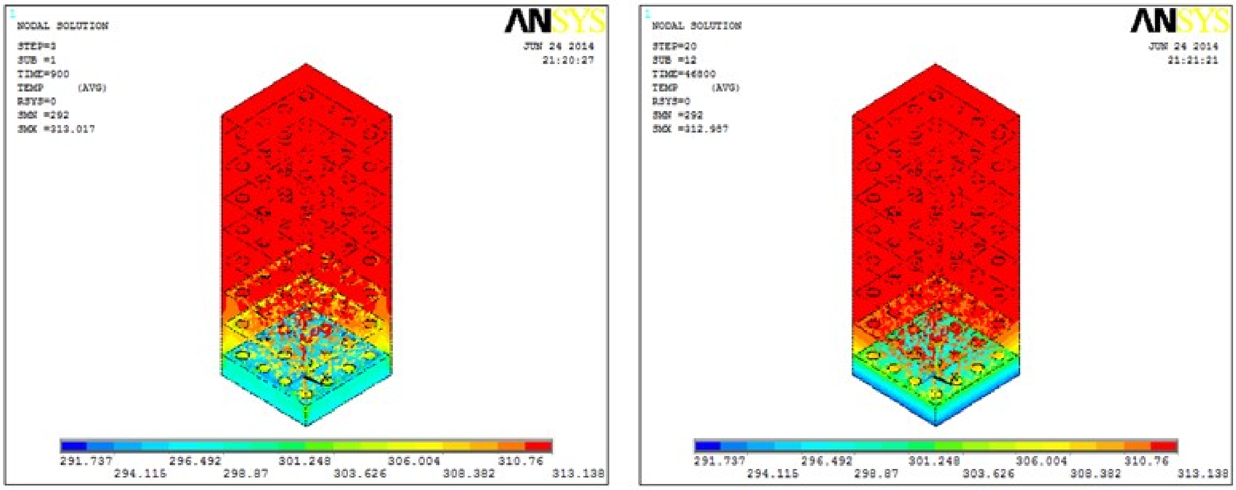
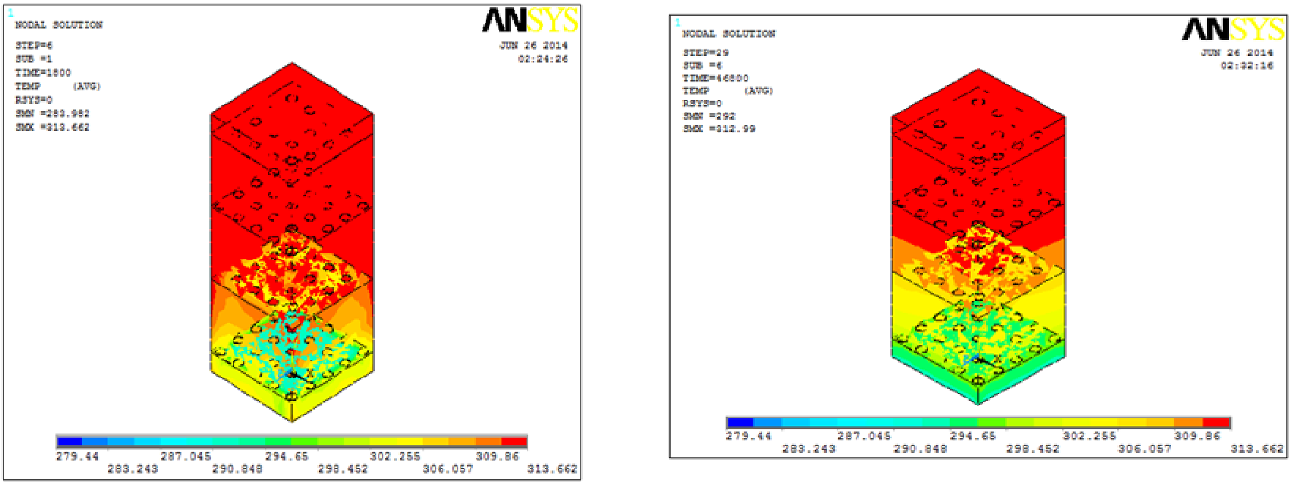
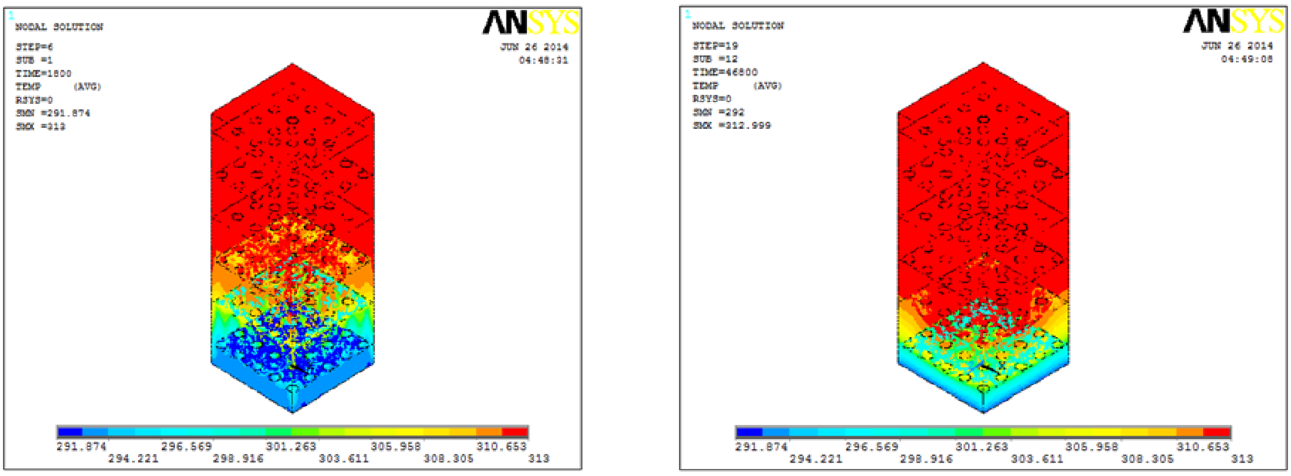


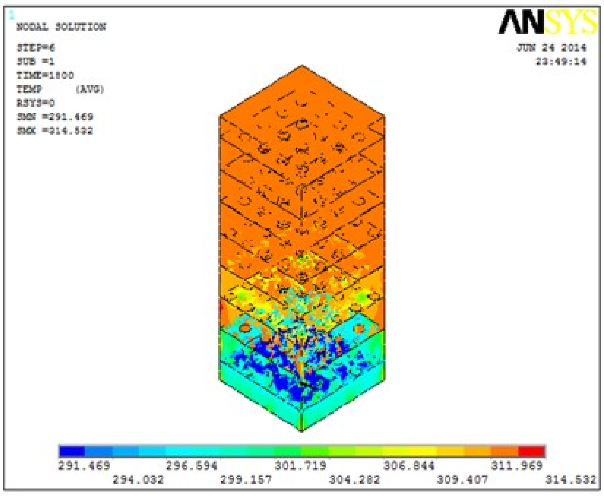
Figure (10): Predicted temperature contours for tank fitted with 4, 6, and 8 inline obstacles of 16% O.A.P

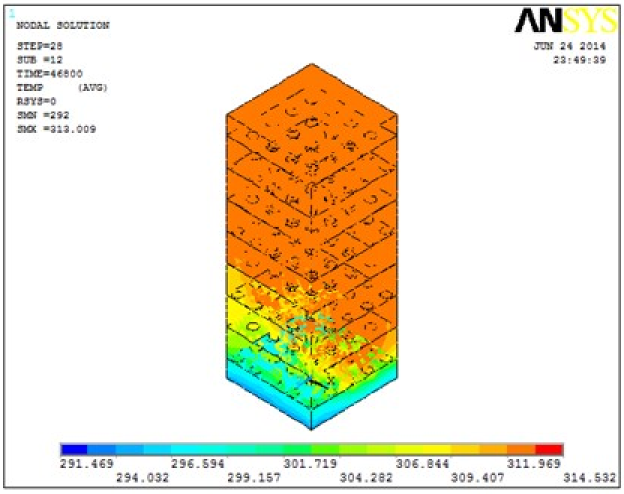


b Four P.O.



b- Six P.O.



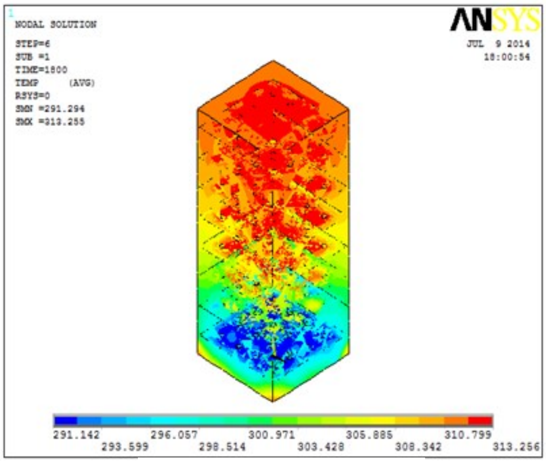


c- Eight P.O.

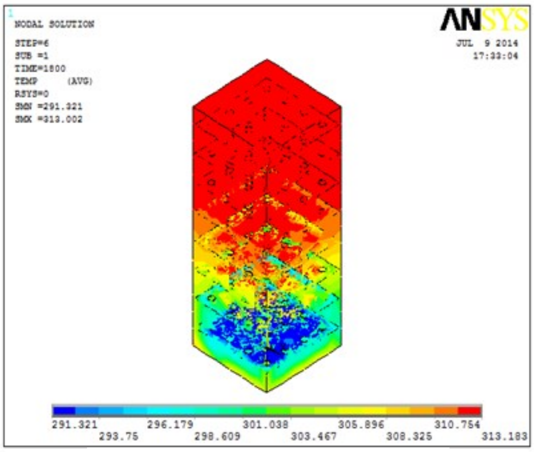
Figure (11): Predicted temperature contours for tank fitted with 4, 6 and 8 staggered obstacles of 16% O.A.P

Figures(12) and **(13)** illustrate temperature contours of storage tank with (8) perforated obstacles at different opening area percentages of(3.14%,7%, 12%, 16%, 20% and 44%)with inline arrangement during charging and standby mode respectively. It can be concluded that the decrease of O.A.P leads to enhance thermal stratification for both modes. However, the optimum O.A.P. is found to be between (7% to 20%) from the numerical model results

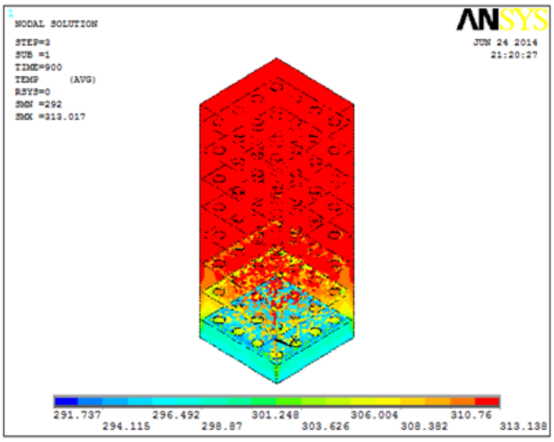
The effect of perforated obstacles number on temperature distribution along tank height is presented in **Figure(14)** for charging mode and standby modes respectively. For inline arrangement the results indicated that thermal stratification is found to increase with perforated obstacles number. Different response for the same number of P.O. and O.A.P. is observed for staggered obstacles as shown in **Figure(15).**



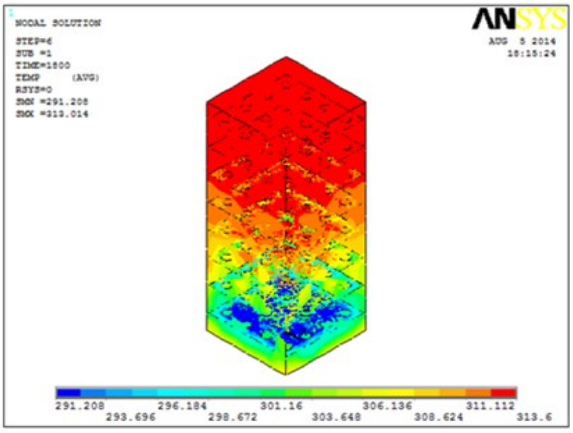
a- O.A.P. of 3.14%



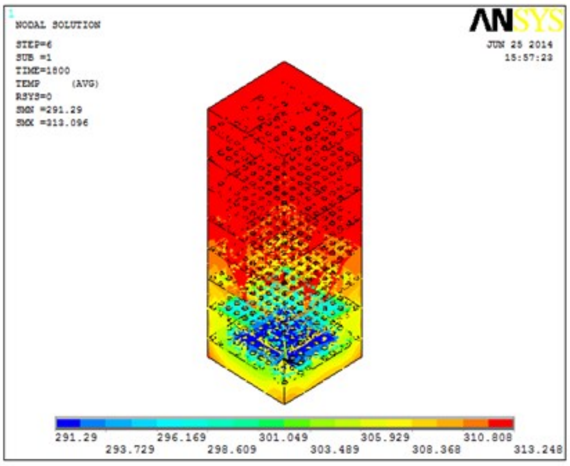
b- O.A.P. of 7%



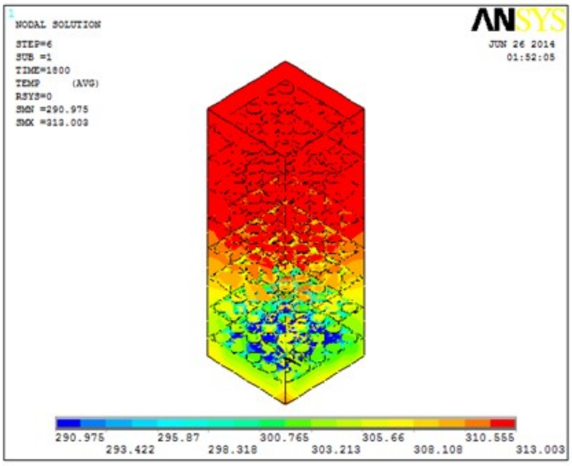
c- O.A.P. of 16%



d- O.A.P. of 12%

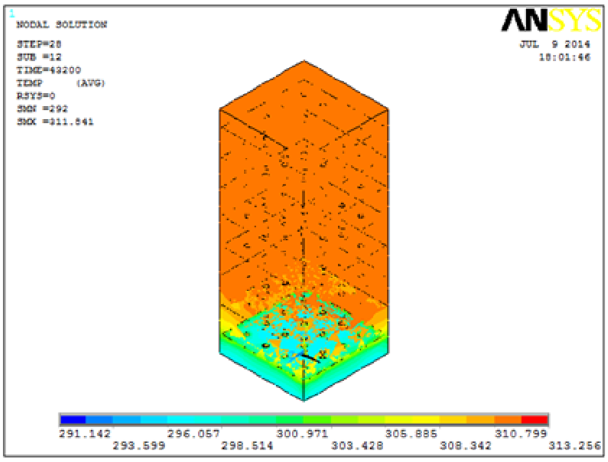


e- O.A.P. of 20%

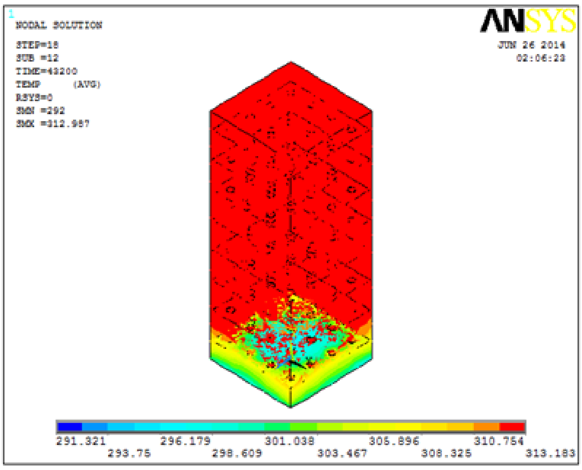


f- O.A.P. of 44%

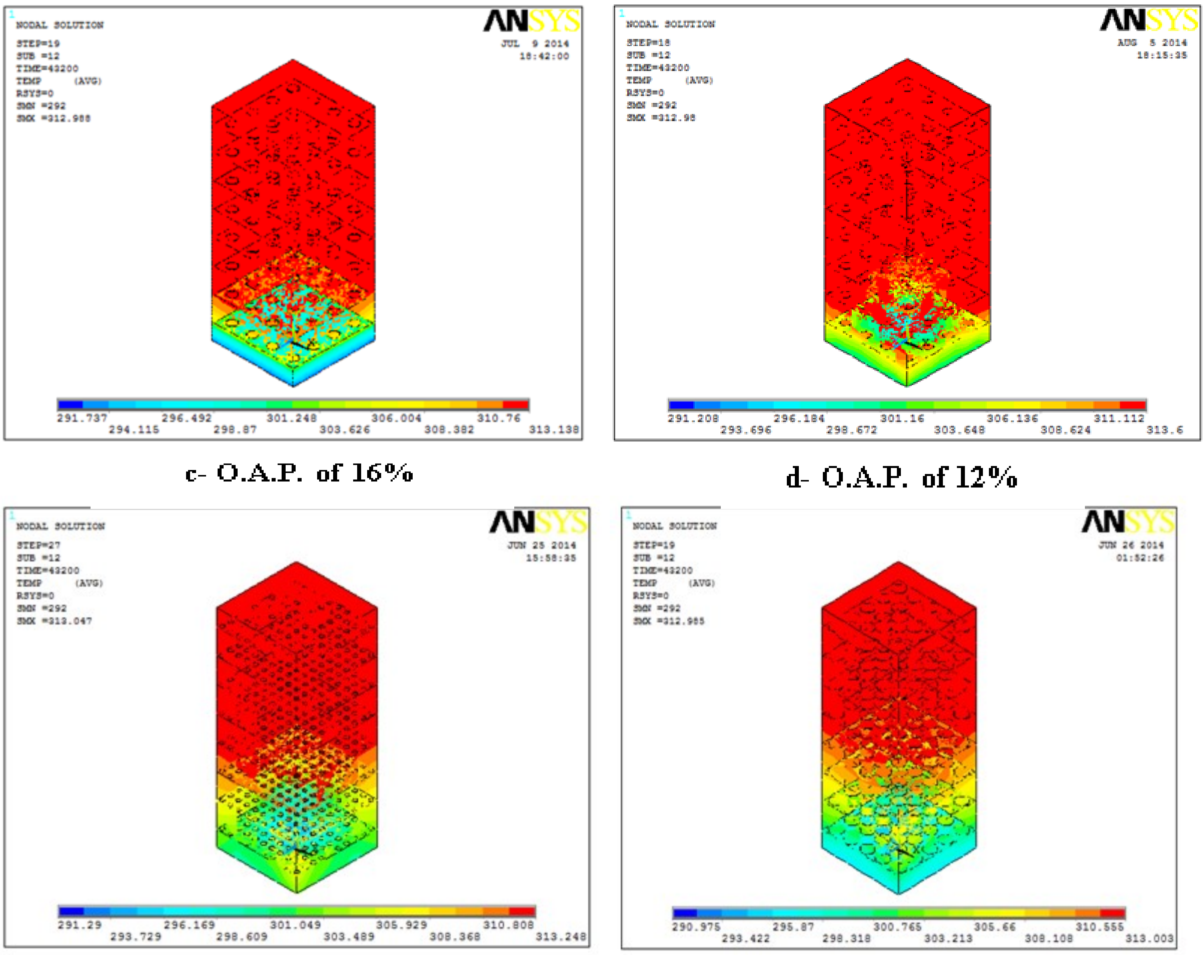
Figure (12): Predicted temperature contours for tank fitted with different O.A.P during charging mode



a- O.A.P. of 3.14%



b- O.A.P. of 7%



c- O.A.P. of 16%   d- O.A.P. of 12%

e- O.A.P. of 20%   f- O.A.P. of 44%

Figure (13): Predicted temperature contours for tank fitted with different O.A.P during standby mode

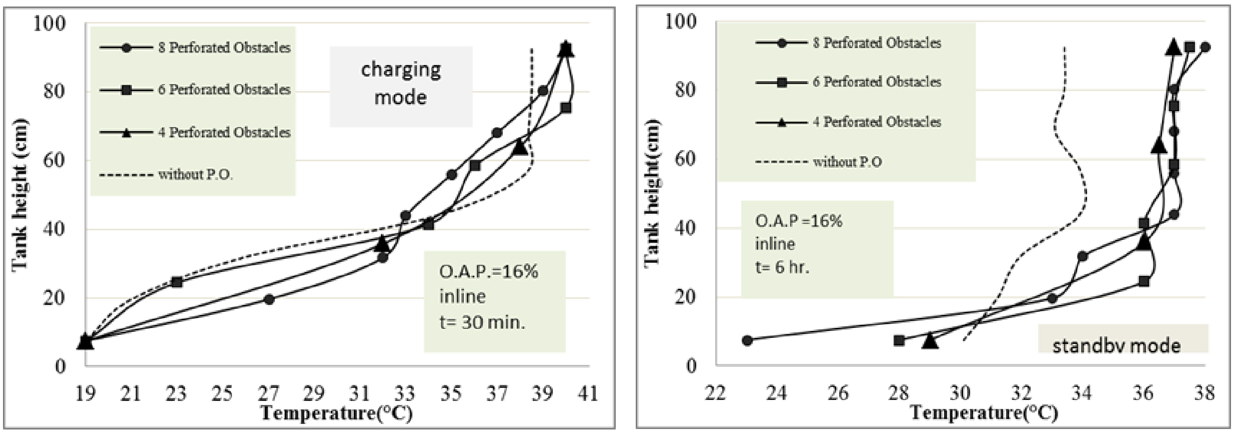


Figure (14): Temperature distribution inside tank with different numbers of inline obstacles

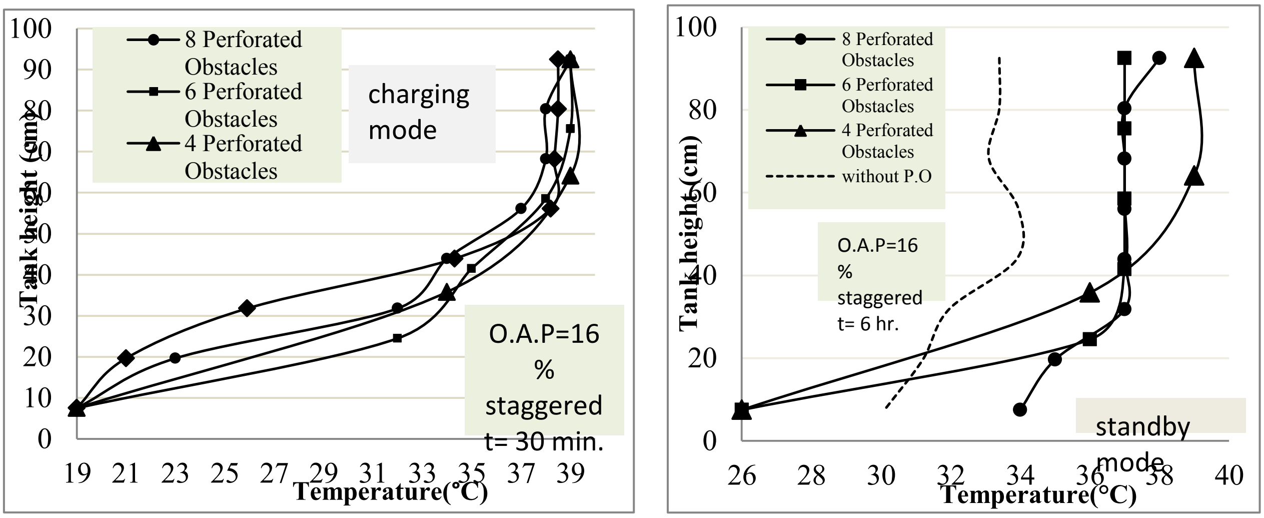


Figure (15): Temperature distribution inside tank with different numbers of staggered obstacles

Using inline arrangement shows little better response for enhancing thermal stratification than using staggered arrangement during charging mode. Also higher thermal stratification could be achieved for tank fitted with six obstacles of staggered arrangement during standby mode. This is could be related to staggered arrangement that leads to higher thermal mixing between water layers than that of inline arrangement. Therefore the ability of inline perforated obstacles to enhance thermal stratification is found to be greater than that of staggered arrangement at same O.A.P.

The effect of O.A.P on thermal stratification for same number of holes per obstacle and same holes center position has been shown in **Figure(16)** for inline (3.14%, 7%, 16% and 44%) O.A.P.

Figure(17) illustrates comparison between temperature history during standby mode for tank without perforated obstacles and tank with 20% O.A.P. of AL. P.O. It is clear that after 12 hr. there was no significant difference between the temperatures of the layers for tank without P.O., while a high degree of thermal stratification identified for tank with inline 20% O.A.P. by lower temperatures near the lower part of the tank and higher temperature at the top. It can be noted that the addition of perforated obstacles reduces thermocline zone thickness and restricts its increasing. A good thermal stratification is still exists even until 12 hr. of standby mode .

Figure(18) illustrates the temperature distribution along horizontal direction of the middle part of tank during charging and standby modes. The figure shows that there is no noticeable temperature change along the horizontal distance of the tank during both modes.

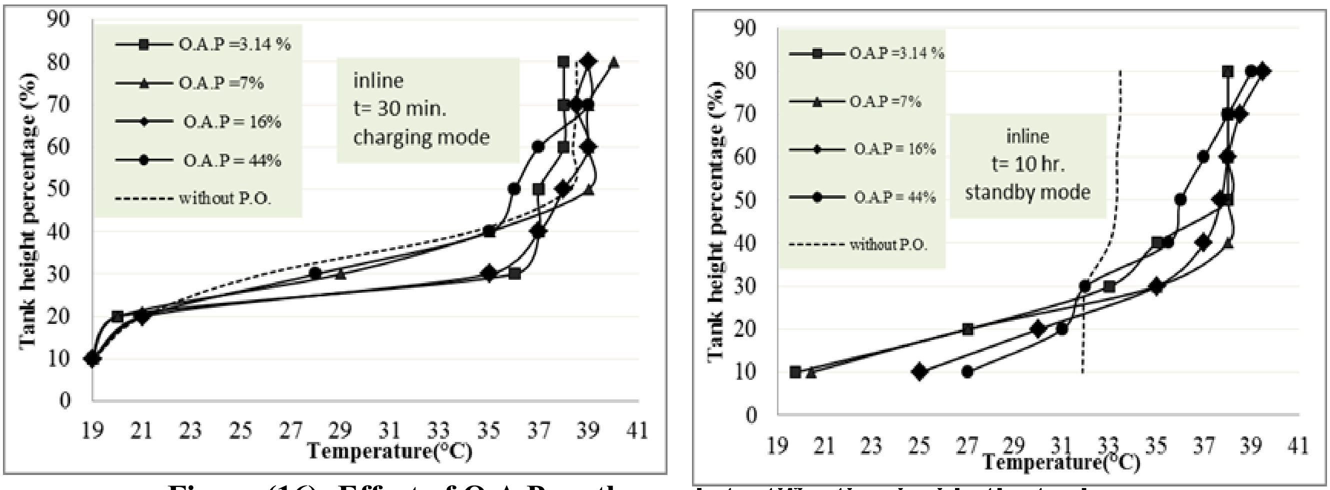


Figure (16): Effect of O.A.P on thermal stratification inside the tank

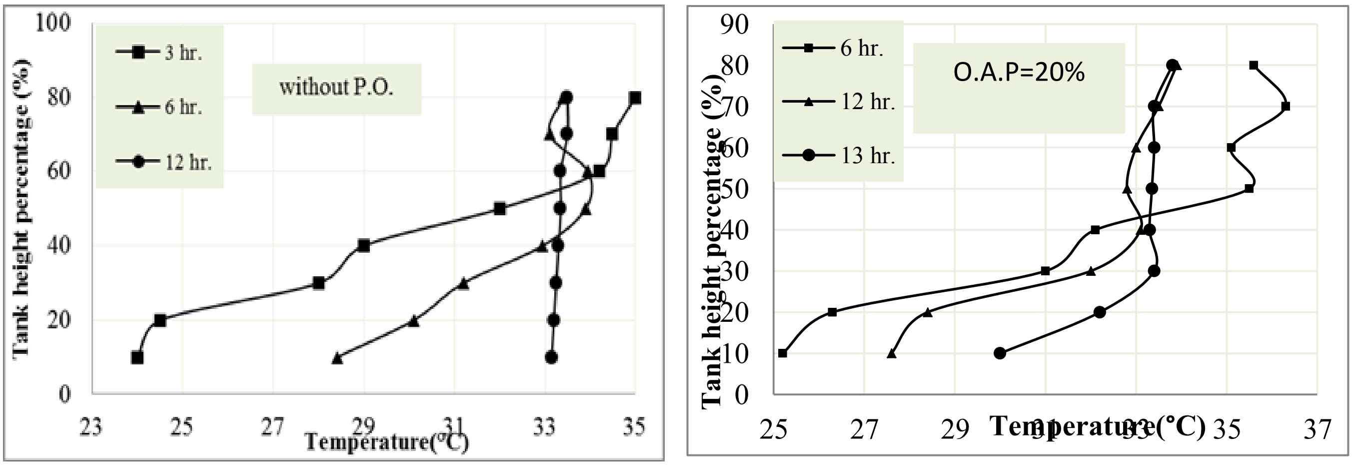


Figure (17): Transient comparison between temperature profiles of tank without P.O. and with 20% O.A.P. of AL. P.O during standby mode

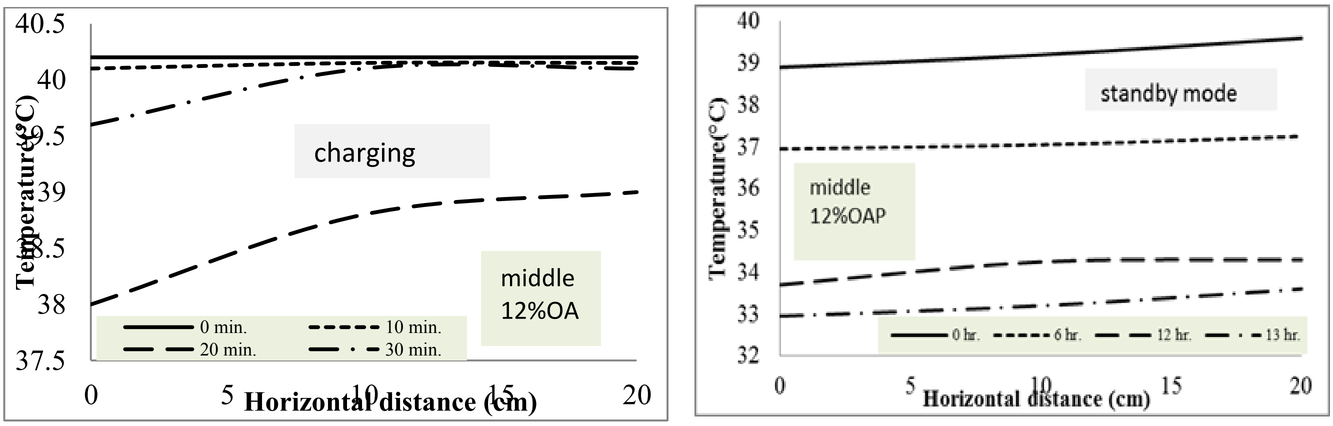


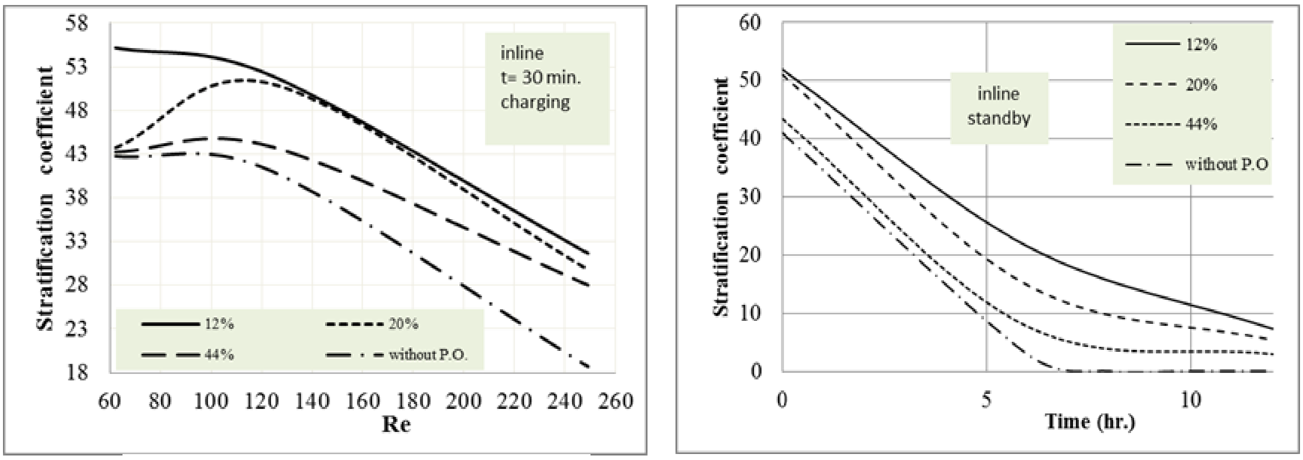
Figure (18): Temperature distribution along horizontal direction at the middle part of the tank height during charging mode

Figure(19) shows the effect of O.A.P with inline arrangement on stratification coefficient for both charging and standby modes. It is clear that the obstacles with (12%-20%) O.A.P. provide the optimum value of stratification coefficient.

However, after sixth hour of standby mode, the stratification coefficient value tends to be close to zero for tank without P.O. (i.e. the tank is thermally mixed).The same behavior is found for stratification number during both charging and standby modes as shown in **Figure(20)**.

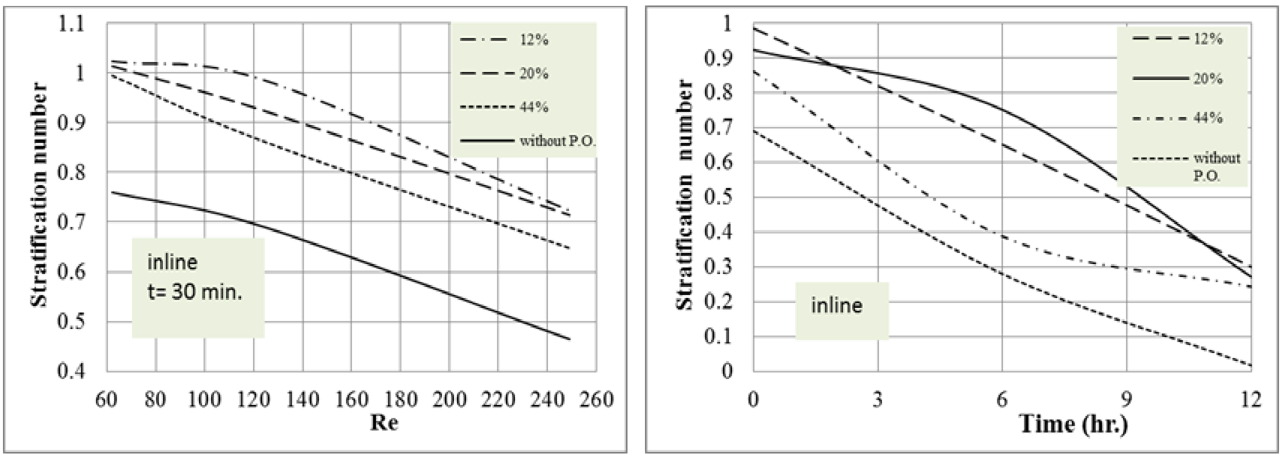
Figure(21) illustrates the effect of arrangement type of perforated obstacles on thermal stratification inside tank. It is clear that, inline opening area arrangement exhibited higher thermal stratification.

The reason of this behavior could be related to the staggered arrangement that led to more thermal mixing which supports heat transfer between the water layers along the tank height



a: charging mode b: standby mode

Figure (19): Effect of O.A.P. on stratification coefficient for Aluminum. P.O



a: charging mode b:standby mode

Figure (20): Effect of O.A.P. on stratification number for Aluminum. P.O.

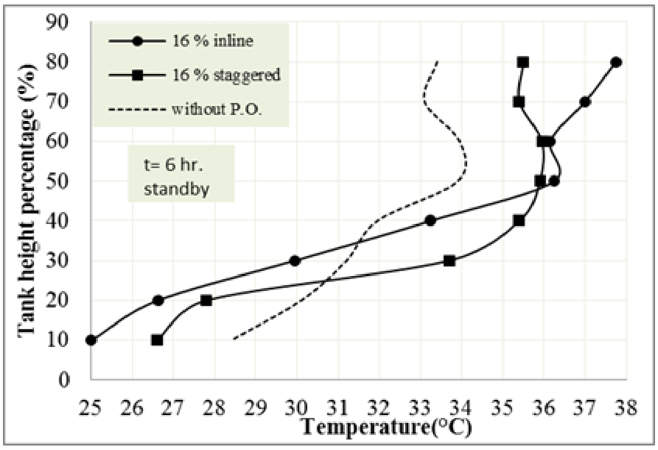
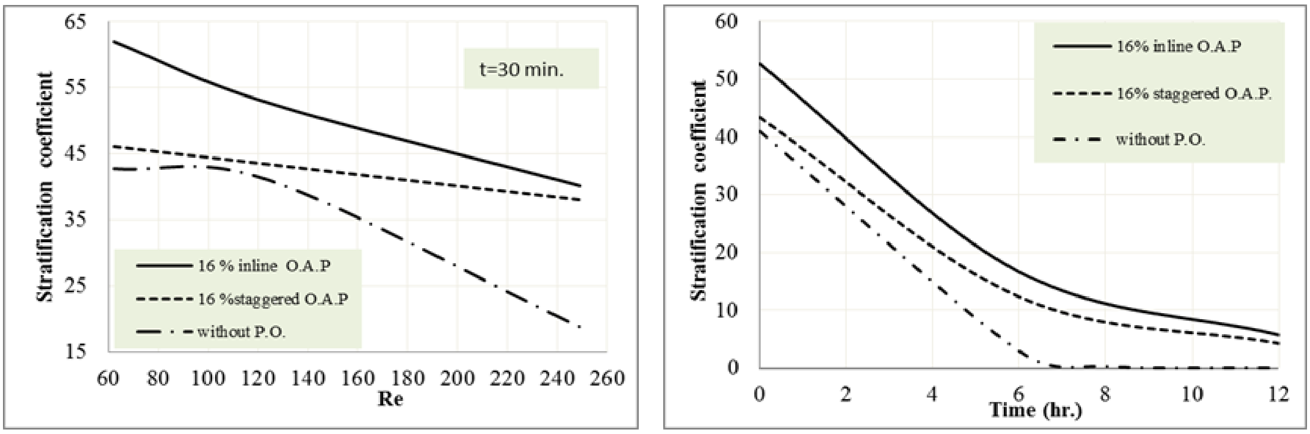


Figure (21): Effect of obstacles arrangement type on thermal stratification for AL.P.O. during standby mode

Figure(22) shows the relationship between stratification coefficient and different opening area arrangements for Al. P.O. It has been noted that the stratification coefficient for inline arrangement is higher than that for staggered arrangement. The behavior of these two opening area arrangements stills obvious during standby mode until the sixth hour where this difference is tend to converge for the rest of standby time. Same behavior for stratification number is found for both arrangements as shown in **Figure(23).**

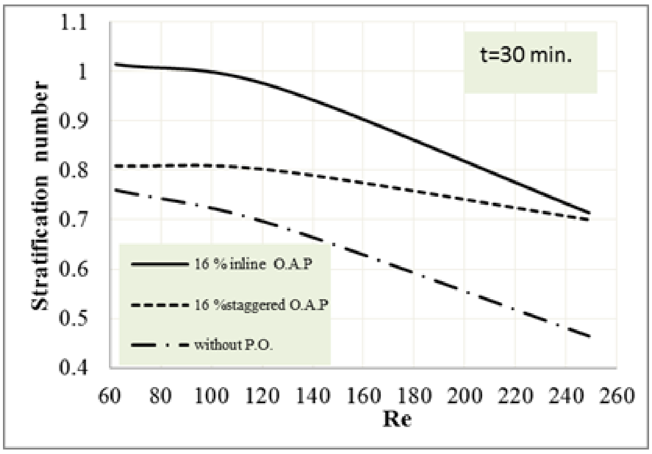
These figures clearly indicate that inline opening area arrangement makes higher stratification enhancement than that of staggered arrangement.



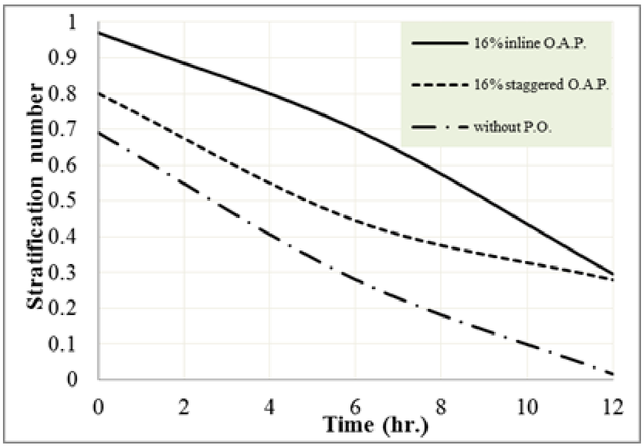
a: charging mode

b: standby mode

Figure (22): Effect of type of obstacles arrangement on stratification coefficient for Al. P.O.



a: charging mode



b: standby mode

Figure (23): Effect of O.A. arrangement on stratification number

Figure(24) shows a comparison between the three various materials that used in this work for fabricating perforated obstacles. As a figure reveals that (F/P Comp.) material is the best type to get higher thermal stratification. However it is noted that there is no obvious relation between obstacles materials and thermal stratification during charging mode.

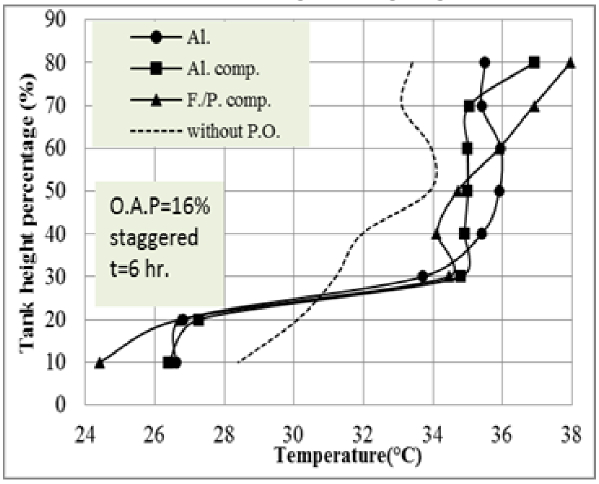


Figure (24): Temperature profiles for different obstacles materials of staggered 16% O.A.P during standby mode

The effect of obstacles material on stratification coefficient and stratification number during standby mode is shown in **Figure(25)**. It can be seen that F/P. comp. obstacles and Alucobond have higher stratification coefficient and stratification number than other types of materials used in this work.

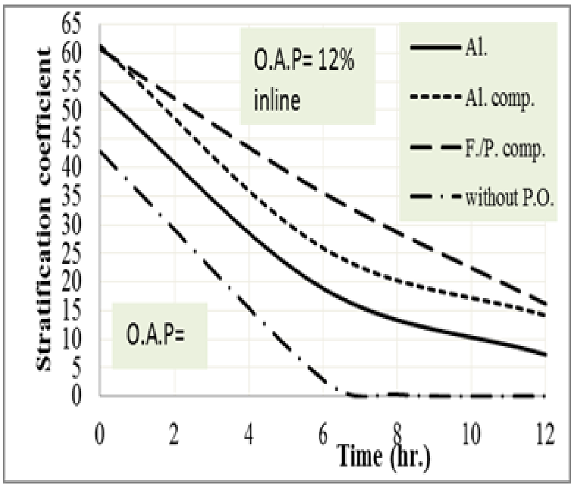


Figure (25): Effect of obstacles material on stratification coefficient and stratification number during standby mode

It can be concluded from these figures that the fiber glass obstacle is found to produce the best response. It seems that the decrease in thermal conductivity leads to decrease heat transfer between vertical water layers. However it's worth mentioning that the effect of perforated obstacle materials on thermal stratification is generally lower than other parameters that have been under investigation, such as Reynolds number, opening area percentage, and opening area arrangement

4- Conclusions

The comparisons between experimental and numerical results indicate that the simulated results show good agreement between numerical and experimental results with maximum deviation $of\ \pm 12.28\%$

In general, as compared with the results of storage without perforated obstacles the thermal stratification of storage tank is enhanced by embedding perforated obstacles into it. The inline opening area arrangement has been found to provide higher thermal stratification than that of staggered arrangement for both charging and standby modes. For inline arrangement, the thermal stratification increases as number of perforated obstacles inside the storage increases during both charging and standby modes and tank fitted with(8) obstacles shows optimum performance. For staggered arrangement, the tank fitted with (six) obstacles shows higher thermal stratification during both charging and standby modes.

The number and location of holes in obstacle has lower effect compared with O.A.P magnitude and its close to be negligible parameter especially at standby mode. The selection of obstacles with (12% to 20%) O.A.P has the most suitable enhancement effect numerically during both charging and standby modes. However the optimum O.A.P. is found to be between (7% to 16%) from both numerical and experimental results. The obstacles material is found to exert little effect on thermal stratification during charging processes and slight enhancement during standby mode. However, the (F /P Comp.) material has been found to be the most preferred material. The temperature change along the horizontal distance of the tank is not noticeable for both charging and standby modes.

The inline, (F/P comp.) material is also found to produce the maximum increase in stratification coefficient and stratification number . Higher values of stratification coefficient and stratification number were found to achieve for (inline 12%) O.A.P. of the (F/ P comp.) perforated obstacles.

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نمذجة الطباقية الحرارية الغير مستقرة في خزانات حفظ الماء البارد

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الخلاصة

الطباقيه الحراريه في خزانات السائل تتدهور بسرعه بمرور الزمن وذلك بسبب الحمل القسري والحمل الحربين طبقات السائل على ارتفاع الخزان لهذا السبب الهدف من هذا العمل هو تحسين الطباقيه الحراريه في خزانات الماء البارد خلال طوري التصريف والخزن وذلك عن طريق اضافه حواجز مثقبه في داخل الخزان باعداد ومواد ونسبه فتحات وترتيب فتحات مختلفه.

تحليل عددي ثلاثي الابعاد انجز باستخدام ANSYS 14.0 package مع Flotran/3D Fluid element 142 لتحليل انتقال الحراره في داخل الخزان . التحليل العددي اختبر لاعداد مختلفه من الحواجز 4 و 6 و 8 مع ترتيب صفي ومتعرج. النتائج الاوليه للتحليل العددي استخدمت لتصميم الجزء العملي . الجزء العملي يتضمن اختبار انواع مواد مختلفه من الحواجز المثقبه من صفائح الالمنيوم ولوائح الالمنيوم المركبه والماده المركبه المدعمه بالياف الزجاج مع نسب فتحات متنوعه وترتيب حواجز متنوع (صفي ومتعرج) .

المقارنه الدقيقه بين النتائج العدديه والعمليه اظهرت توافق جيد مع اكبر مقدار انحراف بنسبه ±12.28 . اوضحت النتائج ان الطباقيه الحراريه تزداد بتقصان رقم رينولد و نسبه الفتحات في الحواجز . عدد ومواقع الثقوب في الحواجز له تاثير قليل مقارنه مع تاثير نسبه الفتحات في الحواجز وان افضل نسبه فتحات تتراوح بين (7٪-16٪). استخدام الترتيب الصفي يظهر تحسين افضل في الطباقيه من الترتيب المتعرج. واعتمادا على النتائج المستخلصه من التحليل العددي والاختبار العملي, افضل طباقيه حراريه وجدت لخزان مزود بثمان صفائح مرتبه صفيا ومصنوعه من الماده المركبه المدعمه بالياف الزجاج وبنسبه فتحات مقدارها 12٪