Enhancing Thermal Stratification in Liquid Storage Tanks During Relaxation Periods *

Asst. Prof. Dr. Ghanim Kadhem Abdulsada
Mechanical Eng. Dept., College of Eng.
Al-Mustansiriya University, Baghdad, Iraq

Lect. Mohammed Hamed Mahmoud
Mechanical Eng. Dept., College of Eng.
Al-Mustansiriya University, Baghdad, Iraq

Abstract

To date, the majority of previous numerical models of the decay of thermal stratification during relaxation time in liquid tanks have ignored the effects of the wall of the storage tank. In this study, a one-dimensional, time dependent mathematical model to predict the degradation of heat in stratified thermocline liquid tank during relaxation periods (i.e. in the absence of external flow) for both cold and hot storage has been developed and tested. The model analyzes the interaction between the liquid inside the tank with its walls by including the effects of heat transfer by convection and conduction through the tank wall.

The numerical simulations have been compared with experimental measurements of water tank. Data were taken on tank fitted with various horizontal porous baffles configuration (including location, number and materials of the porous baffles) and for various initial temperature distributions (stratified and isothermal conditions).

The predicated profiles have been found close to those obtained experimentally especially at the top of the tank. It is found that the walls of the container can have a strong effect in destroying the thermocline. Temperature variation is found to be negligible in the horizontal direction except in the regions very near to the tank wall. Experiments show that better thermal stratification can be obtained by using horizontal porous baffles. The gravel baffles is found to be more effective for enhancing thermal stratification than other two types that have been tested.

Experiments indicate that thermal stratification improves with increasing number of baffles and then flattens. The optimum number of baffles is found to be two baffles. The initial temperature distribution is found to be very important in the subsequent decay of stratification. The natural cooling of an isothermal tank is found to be remaining isothermal and thermal stratification moves forward in the direction to the top of tank.

الخلاصـــــة

الى يومنا هذا، فأن معظم الموديلات العددية السابقة للأنحطاط الطباقية الحرارية خلال زمن الأرخاء في خزانات السوائل قد أهملت تأثيرات جدار الخزان. في هذا البحث، تم تطوير وأختبار موديل رياضي أحادي الأبعاد معتمد على الزمن للتنبؤ بأنحطاط الطباقية الحراريه في خزانات السوائل خلال فترات الأرخاء (اي في فترات غياب الجريان الخارجي) ولكل من الخزان الحار والبارد. الموديل يحلل التفاعل بين السائل داخل الخزان وبين الجدران بتضمين تأثيرات انتقال الحرارة بالحمل والتوصيل خلال جدار الخزان.

تم مقارنة المحاكاة العددية مع القياسات العملية لخزان ماء. تم أخذ البيانات لخزان مزود بأنواع مختلفة من الحواجز المسامية الأفقية (والتي تتضمن موقع, عدد , والمواد المصنوعة منها الحواجز المسامية) ولتوزيعات مختلفة لدرجات الحرارة الأبتدائية (اي عند ضروف ثبوت الحرارة والطباقية).

تم الحصول على نتائج متقاربة بين القيم النظرية والعملية خصوصا في أعلى الخزان. تم استنتاج ان لجدران الخزان تأثير قوي لتدمير الطباقية. تم ايجاد ان تغيرات درجة الحراره بالأتجاه الأفقي يمكن أهماله ما عدا المناطق القريبه من جار الخزان. التجارب العملية بينت انه يمكن الحصول على طباقية حرارية افضل بأستعمال حواجز مسامية أفقية. حواجز الحصو ظهرت انها أكثر فعالية لتحسين الطباقية الحرارية من النوعين الآخرين التي تم اختبارها.

بينت التجارب ان الطباقية الحراريه تزداد بأزدياد عدد الحواجز ثم تثبت. تم ايجاد ان العدد الأمثل للحواجز هو أثنان. تم استنتاج ان توزيع درجات الحرارة الأبتدائية مهم جداً للأنحطاط اللاحق للطباقية. وجد ان التبريد الحر لخزان ثابت درجة الحرارة يبقى ثابت درجة الحرارة، وان الطباقية الحراريه تتحرك للأمام بأتجاه أعلى الخزان.

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1. Introduction

Thermal stratification, or thermocline, refers to the phenomena of holding layers of fluid at different temperatures within one enclosure. Achieving and maintaining a thermocline is essential to ensure that heat transfer fluid will be stored and used at the desired temperature (Marafie et. al.) [1]. Stratification in liquid tanks can be achieved through the elimination of mixing during relaxation periods; otherwise natural convection currents will destroy the temperature layers.

Thermal stratification in liquid tanks is an important parameter in several industrial processes, such as industrial food production and tanks for energy storage such as that due to solar energy collection. In solar energy storage systems that employ water for sensible heat storage, the thermal stratification of the water tank is often employed for improving the efficiency of the collection and storage system. Also, heat removed from industrial units, such as furnaces and ovens, frequently employs water, which is heated during the energy rejection process and is then discharged into water tank.

There are substantial benefits to the use of water tank thermal storage in both heating and cooling. For example, in solar space heating systems, the energy stored during the day can make solar energy available at night for heating. Also, for large air-conditioning systems, chilled-water storage unit is used at night during hours of maximum coefficient of performance, and using this chilled water at the next day (or in the hours of electricity cutoff) to meet the load demand.

The design of such systems, demands an understanding of the thermal stratification and transient temperature field that arises in liquid tanks during relaxation period (i.e. in the absence of external flow). For example, in solar energy water tanks it is very important to determine how thermal stratification decay in the absence of flow, such as at night.

The aim of this work is to introduce a one-dimensional analysis to determine, at any time, the wall and liquid temperatures profiles inside liquid tanks, to predict the influence of the walls thermal conductivity on the thermal stratification, and investigate the influence of adding various horizontal porous baffles inside tank on the decay of the thermal stratification for both partially charged and isothermal storage systems after various time intervals in the absences of an external flow (i.e. after the input of energy into the tank has been stopped).

2. Previous Work

Several investigators have considered the problem of thermal stratification in liquid tanks. Cabelli [2] conducted a numerical study of the behavior of a one-dimensional model of liquid tanks and compared his results with the one obtained from two-dimensional model. The discrepancy between the two models has been found to be small and can be neglected.

Hollands and Lightstone [3] noted that stratified liquid tank is not completely understood and research is required to develop and thoroughly test devices that minimize the effects of destratification.

Lin and Armfield [4] investigated numerically the cooling and stratification processes of an initially homogeneous fluid by natural convection in a vertical circular cylinder.

Leal and Ismail [5] presented a numerical model for a cylindrical thermal storage tank. The numerical solution was realized using the control volume technique. However, Leal and Ismail [5] have neglected the effect of the tank wall in the numerical analysis.

Yee and Lai [6] studied the effects of adding a porous manifold on the thermal stratification in liquid storage tanks for range of Richardson number from 0.01 to 100.

Marcondes et. al. [7] studied the cooling by laminar natural convection of a stainless steel reservoir containing hot water at a constant initial temperature.

3. Mathematical Model

Let the height of the tank be H and let X be the vertical distance from the top of the tank to some arbitrary point within the tank. Assuming one-dimensional system, the temperature distribution within the tank, T(X,t), is governed by the partial differential equation,

$$\rho_L . C_L . \frac{\partial T_L}{\partial t} = \frac{\partial}{\partial X}\left(K_L . \frac{\partial T_L}{\partial X}\right) - \frac{h.P}{A}(T_L - T_w) \quad \text{.................................. (1)}$$

For the present analysis, it will be assumed that for horizontal cross-section, the thermal conductivity is constant. Hence equation (1) becomes:

$$\frac{\partial T_L}{\partial t} = \alpha_L . \frac{\partial^2 T_L}{\partial X^2} - \frac{h.P}{\rho_L . C_L . A}(T_L - T_w) \quad \text{...................................... (2)}$$

The resulting finite-difference equation for the liquid can be re-written as follows:

$$\left[T_{L\,X}^{\,t+1} - T_{L\,X}^{\,t}\right] \Big/ \Delta t = \frac{\alpha_L}{(\Delta X)^2}\left[T_{L\,X+1}^{\,t+1} - 2T_{L\,X}^{\,t+1} + T_{L\,X-1}^{\,t+1}\right] - \frac{h.P}{\rho_L . C_L . A}\left[T_{L\,X}^{\,t+1} - T_{w\,X}^{\,t+1}\right] \quad \text{........................... (3)}$$

In most practical applications, the aspect ratio of the wall (H/δ) is very large, and the wall can be treated as a fin. The external side of the fin is insulated, while the internal side discharges heat to the liquid at a rate determined by the local temperature difference between the wall and the liquid. The governing equation for the wall then be:

$$\rho_w . C_w . \frac{\partial T_w}{\partial t} = K_w . \frac{\partial^2 T_w}{\partial X^2} + \frac{h}{\delta}(T_L - T_w) \quad \text{..................................... (4)}$$

The finite-difference approximation for the tank wall can be represented as:

$$\frac{\rho_w . C_w}{\Delta t}\left[T_{w\,x}^{\,t+1} - T_{w\,x}^{\,t}\right] = K_w . \left[T_{w\,X+1}^{\,t+1} - 2T_{w\,x}^{\,t+1} + T_{w\,X-1}^{\,t+1}\right] \Big/ (\Delta X)^2 + \frac{h}{\delta}\left[T_{L\,x}^{\,t+1} - T_{w\,x}^{\,t+1}\right] \quad \text{................ (5)}$$

The boundary and initial conditions for above equations are:

$$\text{at } X=0 \text{ and } X=H: \ \frac{\partial T_L}{\partial X} = \frac{\partial T_w}{\partial X} = 0 \quad \text{.. (6)}$$

$$\text{at } t=0: \ T_w = T_{w_{initial}} \text{ and } T_L = T_{L_{initial}} \quad \text{.. (7)}$$

The solution of the set of above equations is accomplished with a time marching method to obtain the temperature distributions for both liquid and tank wall. The thermal conductivity variation of water is assumed linear (Ong) [8] and represented by:

$$K = 0.575578 + \left[0.00129617\,(T_L)\right] \quad \text{.. (8)}$$

4. Experimental Work

The experimental study was carried out in water contained in an insulated tank of horizontal dimensions 49×35cm and a height of 84cm. The tank rests on wooden base positioned on the ground to minimize the energy loss to the earth. Temperature sensors were mounted on a wooden (low conductivity) support so that water and wall temperatures could be measured along a vertical plane.

To obtain various initial temperature distributions for the water, the tank was stratified by adding hot water at the top of cold water contained in the tank. The initial temperature distribution could be varied by varying the hot water temperature and the volume of hot water added. Generally, three testing schemes were done, in scheme (I) , the upper half of the tank is filled with hot water (from 60 to 85°C) and the bottom half is filled with cold water (from 15 to 26°C). In scheme (II), the bottom half of the tank is filled with hot water and the upper half is filled with cold water. In scheme (III), all the storage tank is initially filled with hot water (from 55 to 75°C), i.e. isothermal scheme.

The filling of the tank produces fluid motion that persists for some time, and may affect the results. It has been determined that after about three minutes of waiting time between fillings and test running, the detrimental vertical motion had dissipated. In general, tests were started after five minutes of filling and the decay in the temperature distribution beyond this point is studied.

In an attempt to obtain improved thermal stratification, the storage tank has been divided into two to four sections by one to three removable porous baffles fitted inside tank as shown in **Fig.(1)**.

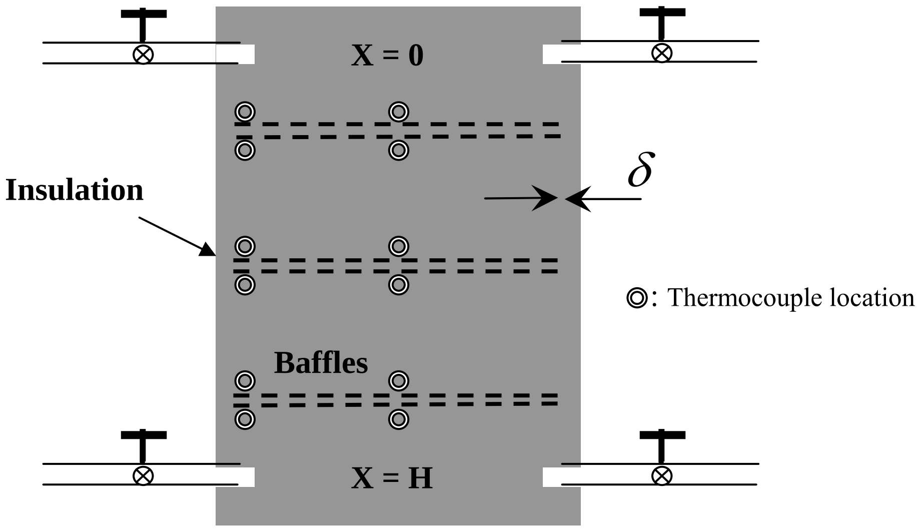

Figure (1) Water tank with removable porous baffles

Three types of baffles material have been tested. Type (1) consists of a pair of drilled plates. Type (2) consists of a pair of drilled plates enclosing drilled corkboard. Type (3) consists of a pair of drilled plates enclosing gravel bed (1.2 to 2 cm diameters). Each type of baffles had the same thickness and the same equally spaced holes producing an opening area of 17% of the total area. About 35% of the measurements were repeated to check the accuracy of the experiments.

5. Results

During thermal relaxation, a comparison between theoretical and experimental temperature profiles for stratified initial temperature distribution (at t=0) with sharp temperature gradients in the middle region (i.e. for scheme I and scheme II) are shown in **Figs.(2)** and **(3)** for water and in **Figs.(4)** and **(5)** for tank wall. For scheme (I), the numerical results were higher than experimental ones except near the tank bottom. However for scheme (I), a lower heat transfer coefficient may be expected near the tank bottom due to lower temperatures. This would explain the lower numerical results as compared to experimental data observed in this region.

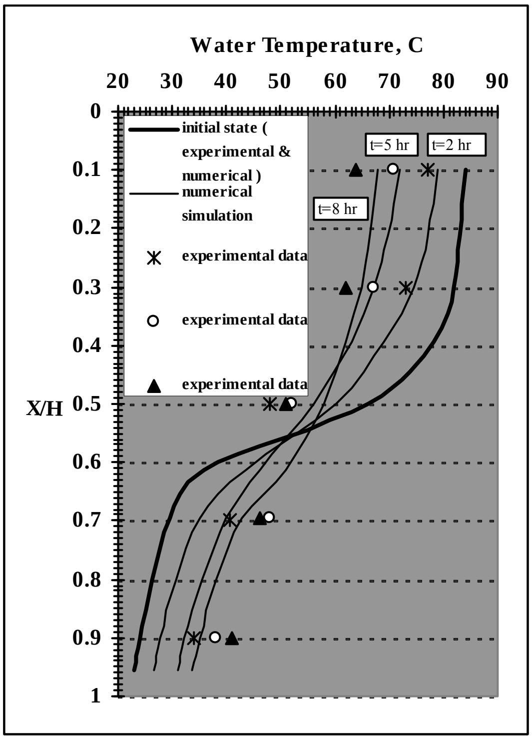

Figure (2) Comparison between the numerical solution and experimental temperature distribution for water during relaxation time of scheme I

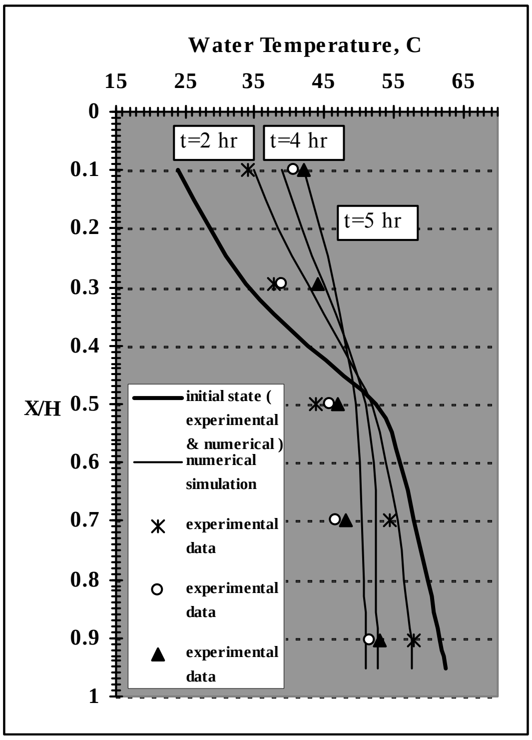

Figure (3) Comparison between the numerical solution and experimental temperature distribution for water during relaxation time of scheme II

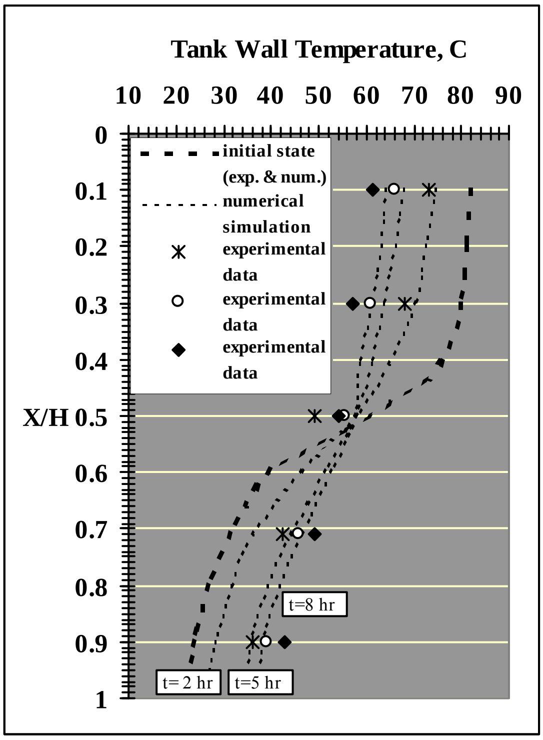

Figure (4) Comparison between the numerical solution and experimental temperature distribution for tank wall during relaxation time of scheme I

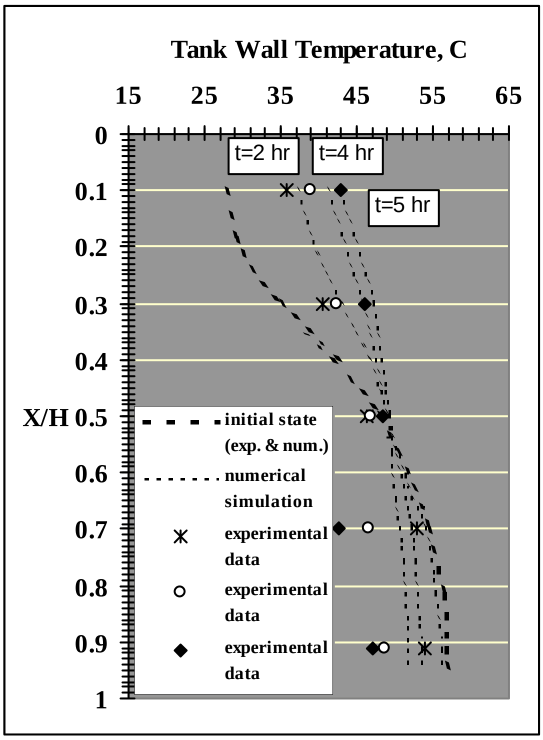

Figure (5) Comparison between the numerical solution and experimental temperature distribution for tank wall during relaxation time of scheme II

It is noted from **Fig.(2)** that as time elapses, the upper region temperature decreases, while the bottom region temperature increases. The thermal gradients in the central region decreases with time to make isothermal region. The depth of the isothermal top layer decreases with time due to heat loss to the deeper layers. Initially, the bottom layers temperature increases, but as time elapses it will also start to cool down due to decreasing heat flux input from the upper layers.

In most of the experiments carried out, it is found that the temperature variation in the horizontal direction is negligible except in the regions very near the tank wall. For stratified initial temperature distribution of scheme (I), the wall temperatures are found to be higher than water temperatures in the bottom zone and lower than that of liquid in the upper zone as shown in **Fig.(6)**. In scheme (II), an opposite behavior for the tank wall temperatures has been found as shown in **Fig.(7)**.

So, convection currents seem to be generated at the water-wall interface inside tank. The walls tend toward the average temperature at a faster rate than water. The change in the wall temperature with respect to water will produce a density difference in the water resulting in natural convection. The heat leaked via the tank wall is found to have a major effect on the decay of thermal stratification in water tanks. Therefore, it is very important to cover the inside wall of the liquid tank by an insulating material to decrease the axial heat conduction through tank wall and decrease the decay in thermal stratification.

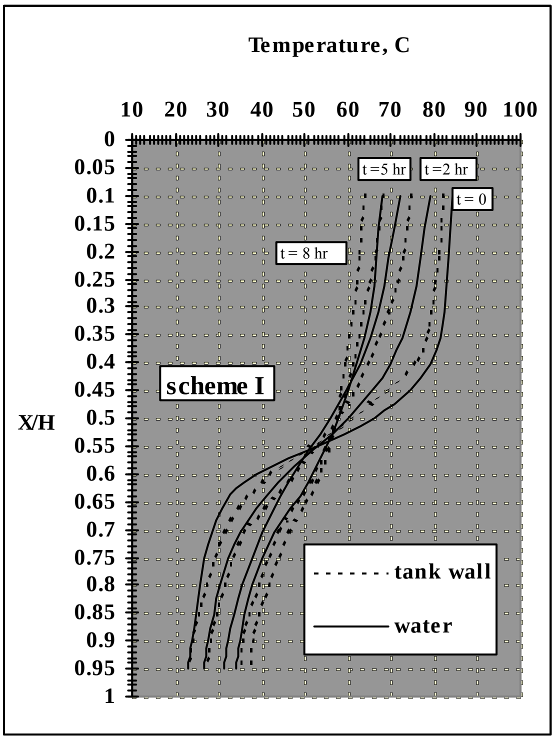

Figure (6) Transient behavior at centerline and at tank wall during thermal decay of stratification of scheme I

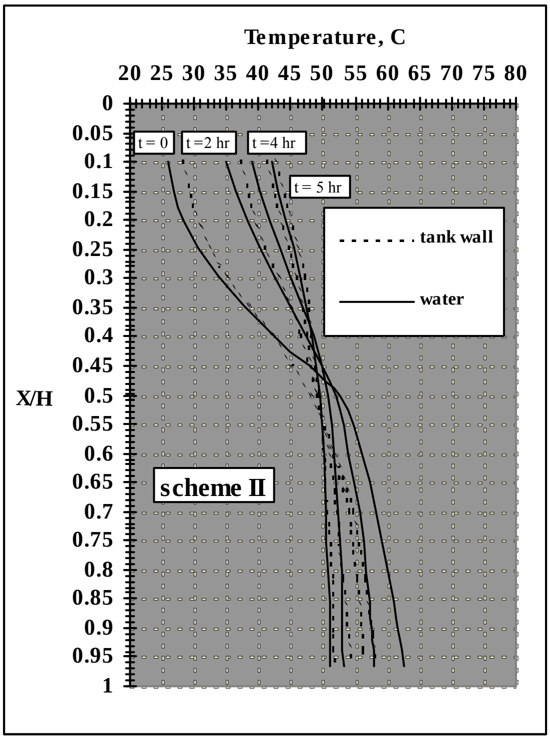

Figure (7) Transient behavior at centerline and at tank wall during thermal decay of stratification of scheme II

Under operating conditions, the typical solar thermal storage, for example, is almost always in a partially charged state (stratified). Such a condition results from the addition and removal of thermal energy at different time of the day. Many other applications, such as industrial liquid storage and household water heater storage involve fully charged (or isothermal) initial state, i.e. scheme (III). **Figure (8)** shows the temperature profiles in the center of the water enclosure for several hours of time. With the progress of time, it's noticed that the stratification moves forward in the direction to the top of tank. It is clear from this figure that a partially charged liquid storage behaves differently from fully charged (or isothermal) storage.

For enhancing and maintaining separation of the warmer and cooler water in the tank, several horizontal porous baffles are fixed inside tank at different locations. The purpose of porous baffles is to aid in minimizing the volume of the transition water between the warmer and cooler regions for natural convection when there is no external flow. Also, these baffles could be used to prevent water from streaming directly from inlet to outlet (when there is a flow inside tank). Many experiments have been done to predict the optimum number of baffles that could be used in water tanks. Experiments indicate that thermal stratification is improved with increasing number of baffles and then flattens. The optimum number of baffles is found to be two for all types of baffles that have been tested. Adding more than two baffles will enhance the stratification in a very limited manner as shown in **Fig.(9)**. Installing three baffles inside tank can gave a very little help to maintain the thermal stratification, but costing and manufacturing difficulties arise. All other experiments for the three schemes indicate a similar behavior as those of **Fig.(9)**.

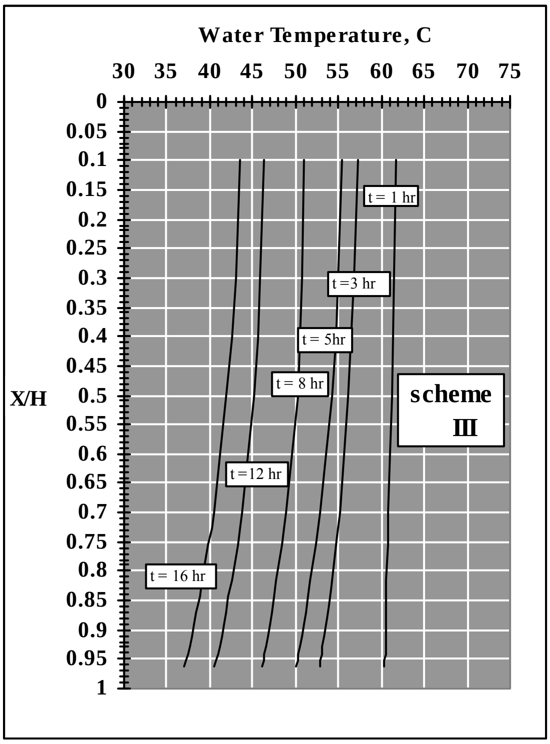

Figure (8) Temperature profiles of water during desertification time of scheme III

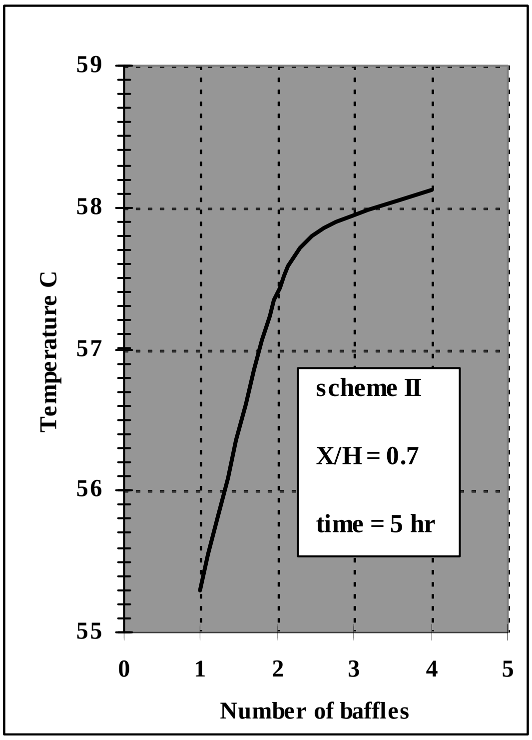

Figure (9) Effect of number of baffles on the decay of temperature inside water tank

To compare the capability of the porous baffles in maintaining thermal stratification, the tank is tested under the same initial conditions (at t=0) for two different boundary conditions, with baffles and without baffles. **Figures (10)**, **(11)** and **(12)** show the effect of adding two baffles on the thermal stratification inside tank for scheme (I), (II) and (III) respectively. Generally, using baffles inside liquid tanks had maintained better thermal stratification than tank with no baffles. For applications that include an operation conditions similar to scheme (I) and (II), thermal stratification could be best maintained with baffles made of materials with low thermal conductivity (corkboard baffles) that decreasing the heat conduction between hot and cold liquid inside the tank as shown in **Figs.(10)** and **(11)**. For isothermal liquid tanks, the use of gravel bed baffles had maintained the thermal energy better than other types of baffles as shown in **Fig.(12)**.

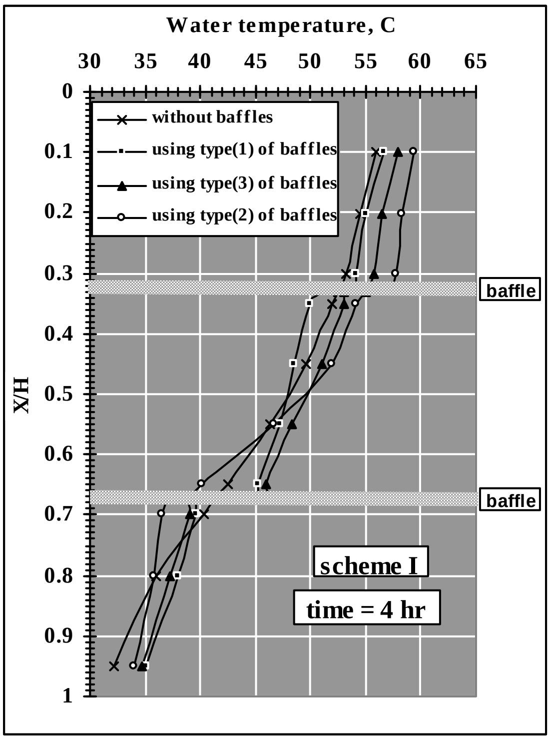

Figure (10) Influence of adding two baffles on the thermal stratification inside tank during desertification time of scheme I

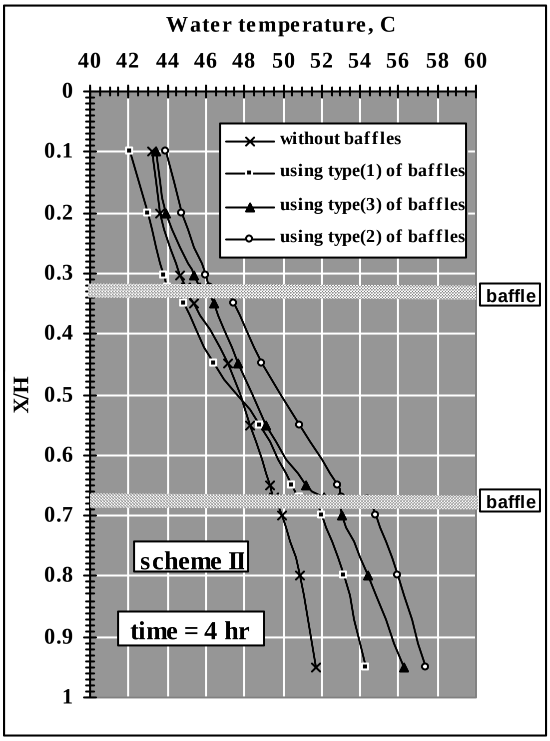

Figure (11) Influence of adding two baffles on the thermal stratification inside tank during desertification time of scheme II

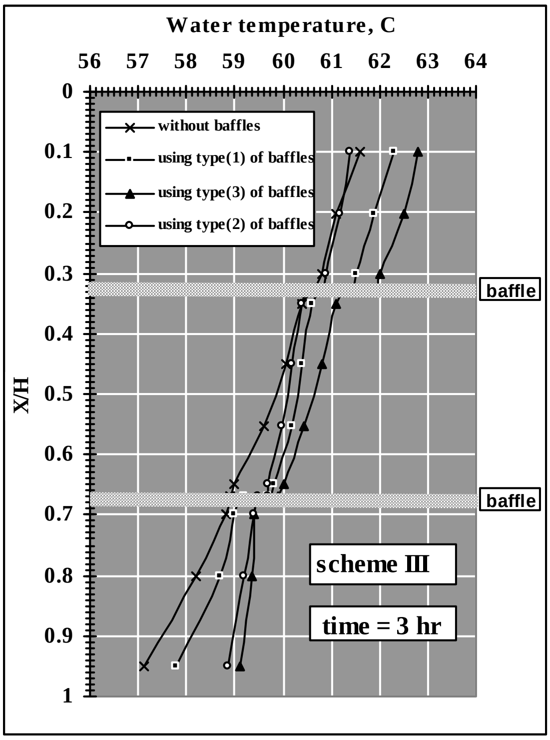

Figure (12) Influence of adding two baffles on the thermal stratification inside tank during desertification time of scheme III

6. Conclusions

A numerical study for natural cooling and heating of a time-dependent thermally stratified liquid tank that including the effect of tank wall has been carried out. The developed numerical model is compared with the experimental data and found to be very satisfactory for the prediction of both liquid and tank wall temperature profiles as a function of time during thermal relaxation period.

Vertical conduction within the tank wall has been found to give rise to natural convection currents during relaxation time. Liquid near the wall is heated or cooled faster than the bulk of the liquid in the tank. The resulting horizontal temperature difference near tank-wall drives a natural convection circulation that leads to a homogenization of temperature. Therefore, for enhancing thermal stratification it is suggested to insulate the tank interior surface to eliminate axial conduction and possible buoyant effects.

The nature of the thermal stratification decay in the absence of any external flow is studied experimentally for different levels of thermal stratification in the liquid tank. The mixing induced by buoyancy has been found to be depending strongly on the initial temperature distribution. The temperature variation in the horizontal direction is found to be negligible except in the regions very near to tank wall. The cooling of an isothermal water tank is also considered and it is found that it continues to remain isothermal for a wide range of tank height and thermal stratification is found to move forward in the direction to the top of tank.

Three types of effective porous baffles, used to enhance thermal stratification of the liquid inside tank, were designed and tested. It is found that the addition of corkboard baffles to the tank improves temperature stratification better than gravel bed or drilled plate's baffles. Experiments indicate that thermal stratification has been improved with increasing number of baffles and then flattens. The optimum number of baffles is found to be two.

7. References

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Nomenclature

A: Cross-sectional area of tank.
C_L: Specific heat of liquid.
C_w: Specific heat of tank wall.
H: Tank height.
h: Heat transfer coefficient between liquid and tank wall.
K_L: Thermal conductivity of liquid.
K_w: Thermal conductivity of tank wall.
P: Perimeter of the tank.
t: Time.
T_L: Liquid temperature.
T_w: Wall temperature.
X: Vertical distance from the top of the tank to some arbitrary point within tank.
α_L: Thermal conductivity of the liquid.
δ: Thickness of the wall.