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EXPERIMENTAL STUDY OF TEMPERATURE STRATIFICATION IN A THERMAL STORAGE TANK IN THE STATIC MODE FOR DIFFERENT ASPECT RATIOS

Abdul Jabbar N. Khalifa, Ayad T. Mustafa and Farhan A. Khammas
College of Engineering, Nahrain University, Jadiriya, Baghdad, Iraq
E-Mail: far_1961ah@yahoo.com

ABSTRACT
Thermal stratified storage tanks are an effective method to improve the efficiency of thermal storage devices that are commonly used in thermal systems when the available energy source is irregular or when a time lag exists between the production and the demand. It has been shown that thermal stratification is affected by a number of factors such as mixing due to the inlet and outlet streams, heat losses to the environment and tank configuration such as the aspect (height to diameter) ratio. Thermal behavior and stratification of hot water storage tanks during the stagnation mode is investigated experimentally in this study for three different aspect ratios (AR) of the tank, namely 2, 1 and ½. The study addresses the change in water stratification during the cool down of the water inside the storage tank of thermal systems in the 85°C to 30°C temperature range, which lies within the operating range of most conventional and solar hot water and liquid based heating systems.

Keywords: stratification, thermal storage, aspect ratio, water tank.

1. INTRODUCTION
When a hot water tank without external flow is subjected to the ambient temperature, a thermal stratification of water is formed in the course of the cooling process. The cold water accumulates at the bottom while hot water ascends to the top of the tank. This phenomenon occurs even if all the water inside the tank is initially at a uniform temperature. It is originated from the fact that, prior to releasing heat to the ambient, the tank wall cools a thin vertical layer of water along the tank wall. Part of this heat is then transferred by diffusion towards the core of the tank. The water of the vertical layer becomes denser than its surrounding and then slips towards the bottom of the tank creating the stratification.

Thermal stratified storage tanks are an effective method to improve the efficiency of thermal storage devices that are commonly used in thermal systems when the available energy source is irregular or when a time lag exists between the production and the demand. Because of simplicity and low cost, sensible heat storage is widely used in such applications, for example in solar energy and refrigeration and air conditioning systems. Water storage tanks are the most attractive options for such systems due to the abundance, low cost and good thermal properties of water. A substantial increase in the total efficiency of the thermal system may be achieved by a good thermal performance of the storage tank, which is determined by the degree of its thermal stratification.

Thermal stratification in storage tanks has been the subject of various experimental and numerical studies [Kandari (1990), Al-Najem *et al.* (1993), Shin *et al.* (2004)]. It has been shown that thermal stratification is affected by a number of factors such as mixing due to the inlet and outlet streams, heat losses to the environment and tank configuration. [Kusyi and Dalibard (2007), Kenjo *et al.* (2007), Zurigat *et al.* (1998), Zurigat *et al.* (1991), Berkel (1996), Al-Najem and El-Refae (1997), Hezagy and Diab (2002), Gupta and Jaluria (1982)]. The results of Fernandez-Seara *et al.* (2007) during static mode indicated that for the first stage of the cooling process following the heating with 2.2 kW, the stratification increased with respect to the stratification at the end of the heating process, later on, the stratification slightly diminished. The decay of the stratification during this cooling process was very low. However, for the cooling process following the heating with heating power of 4 kW, the stratification decreased continuously during the cooling period. The analysis of the stratification revealed that it depends mainly on the initial water temperature profile.

The height to diameter ratio (AR) is a factor that influences stratification [Haller *et al.* (2009)] which may be enhanced through the proper design of tank parameters such as aspect ratio [Walmsley *et al.* (2009)]. A CFD-integrated analysis of a large-scale hot water seasonal heat store was numerically studied by Panthalookaran *et al.* (2007) to identify the effects of aspect ratio, containment shape, internal structures, and containment size on their efficiency. Improvement of the charging-discharging process was noticed with the increase in aspect ratio. Cole and Bellinger (1982), Ismail *et al.* (1997) and Hahne and Chen (1998) concluded that maximum thermal stratification could be achieved inside the storage tank with a aspect ratio of four while Nelson *et al.* (1997) suggested aspect ratio of three for the best thermal stratification. In a study on four thermal storage tanks with aspect ratios of 1.56, 2.06, 3.54 and 4.0, Hariharan *et al.* (1991) observed that aspect ratio values between 3 and 4 were found optimal. The study of Al-Kandari (2004) on five thermal storage tanks with aspect ratios of 1, 2, 3, 4 and 5 confirmed this finding.

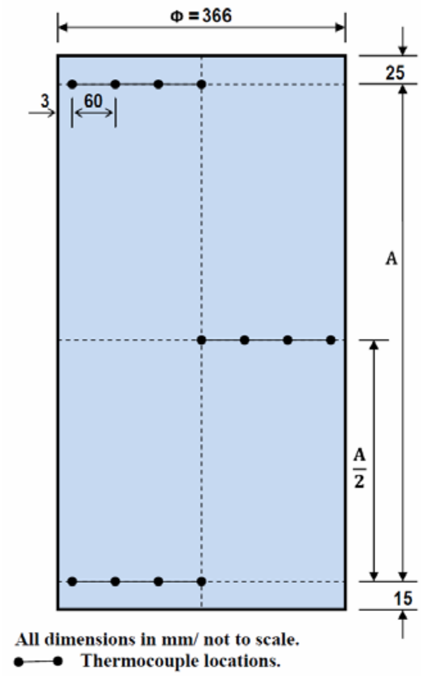
In general, experiments and simulations on hot water heat stores had shown that an increase in the aspect ratio of the heat store lead to better thermal efficiency, the effect of which was remarkable when the aspect ratio was

≤ 3 [Cotter and Charles (1993), Matrawy *et al*. (1996), Ismail *et al*. (1997), Eames and Norton (1998), Bouhdjar and Harhad (2002)].

Thermal behavior and stratification of hot water storage tanks during the stagnation mode is investigated experimentally in this study for three different aspect ratios (AR) of the tank, namely 2, 1 and ½. Tanks having aspect ratios close to these values are thought to be more realistic in the domestic and solar hot water systems compared to the optimum values of 3 and 4 reported in the literature. The study addresses the change in water stratification during the cool of water inside the storage tank of thermal systems for different aspect ratios. The temperature rang investigated of 85°C to 30°C lies within the operating range of most conventional and solar hot water and liquid based heating systems.

2. EXPERIMENTAL SETUP AND PROCEDURE

Laboratory tanks are constructed from galvanized steel sheet 1-mm-thick to study the stratification of water at various aspect ratios. The tanks were not insulated to promote the development of stratification in the tank through heat loss to the surroundings. Three aspect ratios, namely ½, 1 and 2 are investigated. The dimensions of the tanks are shown in Figure-1 together with location of the temperature measurements. Twelve calibrated copper-constantan thermocouples are distributed at three levels in the tank to measure the water temperature using a microprocessor thermometer (range: -100 to 400°C and accuracy ±1%).



Aspect Ratio (AR)	A (mm)
2	715
1	355
1/2	185

Figure-1. Tank dimensions and location of temperature measurements.

The tanks were filled with hot water at around 85°C at the beginning of the test and readings are taken at different time intervals until the water is cooled to around 30-40°C. By this procedure, the development of stratification in hot water storage tanks during the cooling of water can be observed for different aspect ratios at the static mode.

3. RESULTS AND DISCUSSIONS

Figures 2 to 4 show the contour lines during the cooling of water in the stagnation mode for aspect ratios (AR) ½, 1 and 2. Readings from only four time intervals are shown. The isotherms are 0.2°C apart in all these Figures. As the isotherms are expected to be symmetrical around the vertical axis of the cylindrical tank, only the right half of the tank is shown in the Figures. The time variations of the temperature gradients through the tank height for the same aspect ratios are shown in Figures 5 to 7.

In Figures 2 and 5, the time variation of stratification in a tank with an aspect ratio of ½ is shown. It can be seen from Figure-2(a) that the stratification at the top half of the tank is very weak as represented by the vertical line in Figure-5a (degradation in temperature of only 1°C). On the other hand, the stratification at the bottom half of the tank is noticeable, as can be seen also from the same Figure (a decline from 84 to 79.5°C). As the tank loses more heat to the surroundings, the top half of the tank becomes slightly more stratified while the stratification at the bottom half remains almost unchanged as can be seen from Figures 2(b) and 5b. As the heat losses from the tank continue, the stratification in the upper half of the tank becomes more obvious while that in the bottom half remains almost unchanged through the cooling of water as can be seen from Figures 2(c), (d) and 5c, d. The water in the tank kept a steady temperature difference between the top and bottom of around 5°C.

The time variation of stratification in a tank with an aspect ratio of 1 is shown in Figures 3 and 6. It can be noticed from Figures 3(a) and 6a that the stratification in a small part at the top of the tank is weak while that in the rest of the tank is clearly visible. As the tank loses more heat to the surroundings, the stratification in most of the tank, except for a small part at the top, is gradually destroyed. The temperature difference between the top and bottom of the tank is reduced gradually with time from around 20°C in Figure-6a to 14°C in Figure-6b, 7°C in Figure-6c and 5°C in Figure-6d.

In Figures 4 and 7, the time variation of stratification in a tank with an aspect ratio of 2 is shown. It can be noticed from Figures 4(a) and 7a that the stratification is clear in the whole tank. As the tank loses more heat to the surroundings, the stratification in the upper on third of the tank loss stratification gradually while the rest of the tank becomes progressively less stratified as can be seen from the comparison of the lines of temperature gradients b, c and d in Figure-7. The temperature difference between the top and bottom of the tank is reduced gradually with time from around 17°C in

Figure-7a to 15°C in Figure-7b, 10°C in Figure-7c and 8°C in Figure-7d.

Comparison of the stratification in the different aspect ratios show that the degree of stratification in the small aspect ratio (½) remains moderate and almost unchanged with time while that in the larger aspect ratios (1 and 2) is strong and decay gradually with time. The decay however is more noticeable in the aspect ratio 1 than in 2, which may indicate the advantage of the larger aspect ratio in keeping the stratification for a longer period of time.

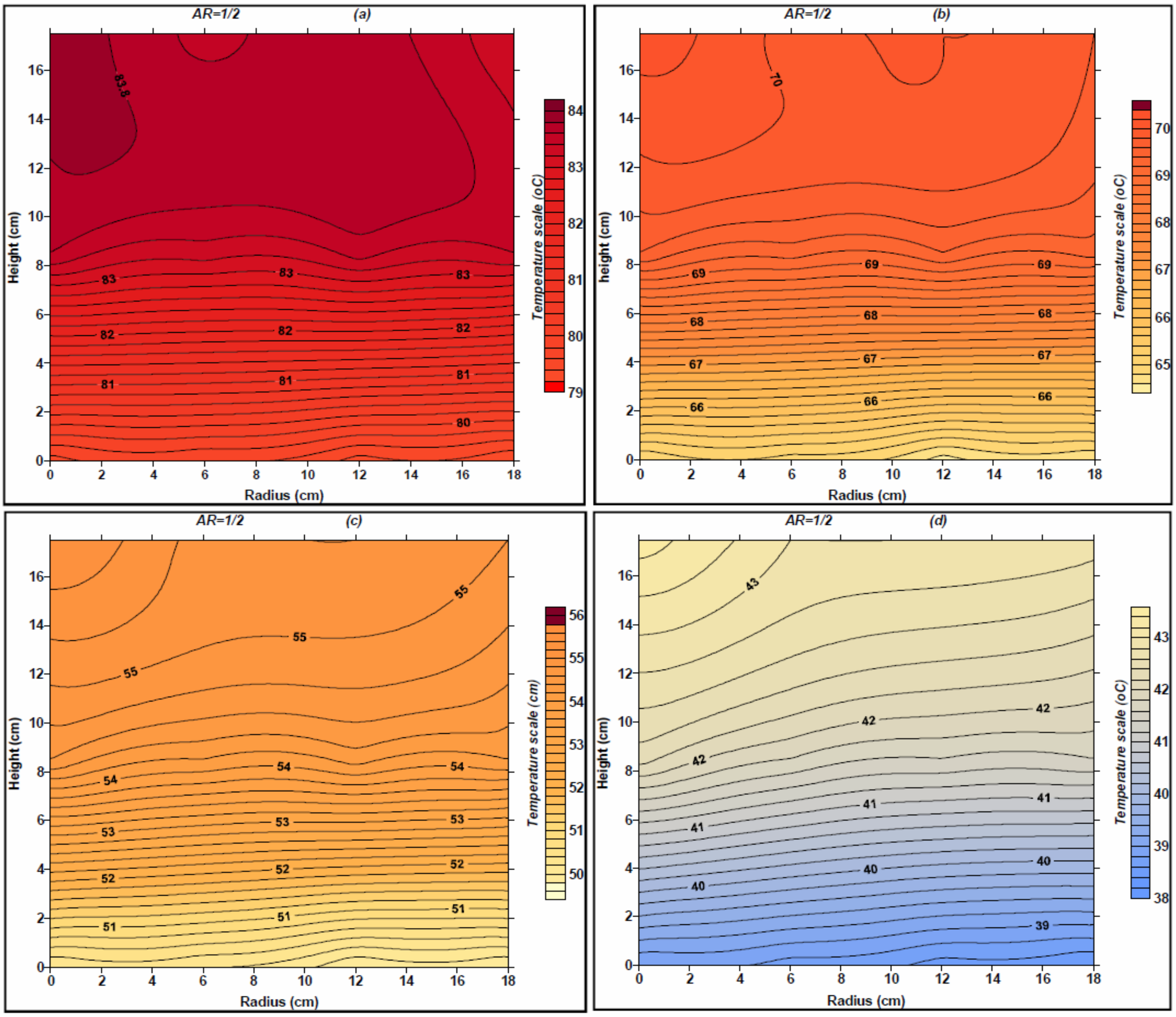


Figure-2. The time variation of the temperature contours for a thermal storage tank with aspect ratio ½.

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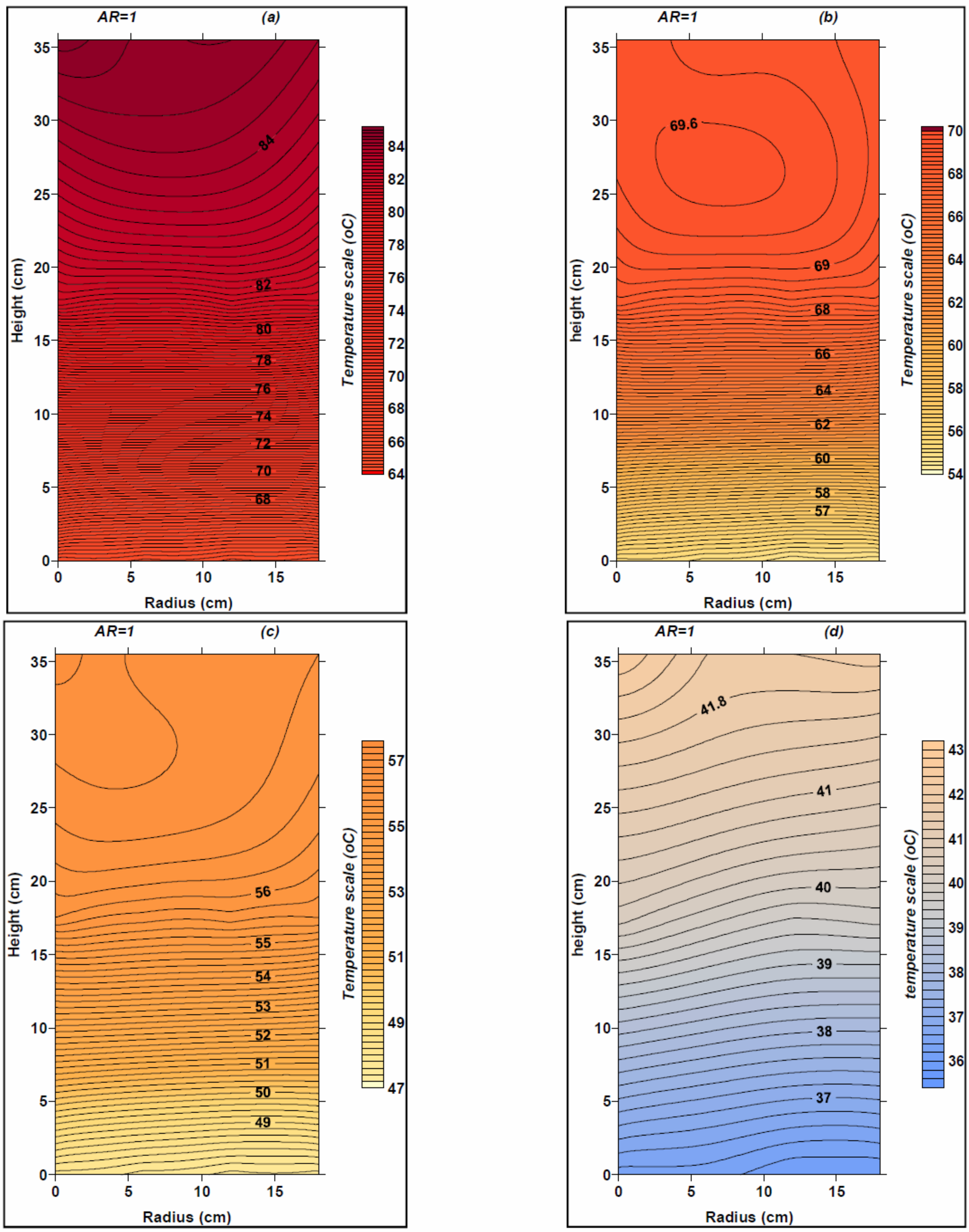

Figure-3. The time variation of the temperature contours for a thermal storage tank with aspect ratio 1.

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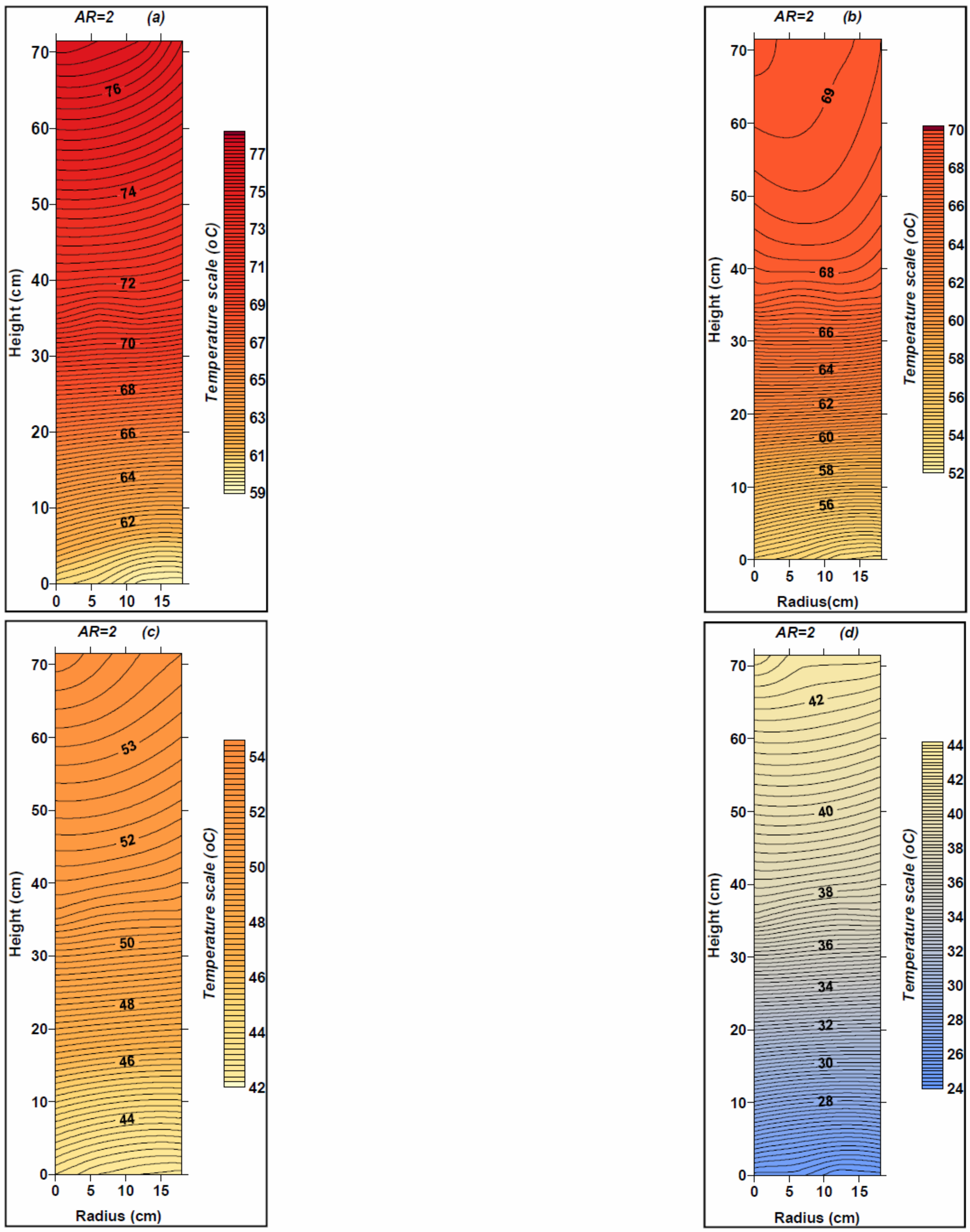

Figure-4. The time variation of the temperature contours for a thermal storage tank with aspect ratio 2.

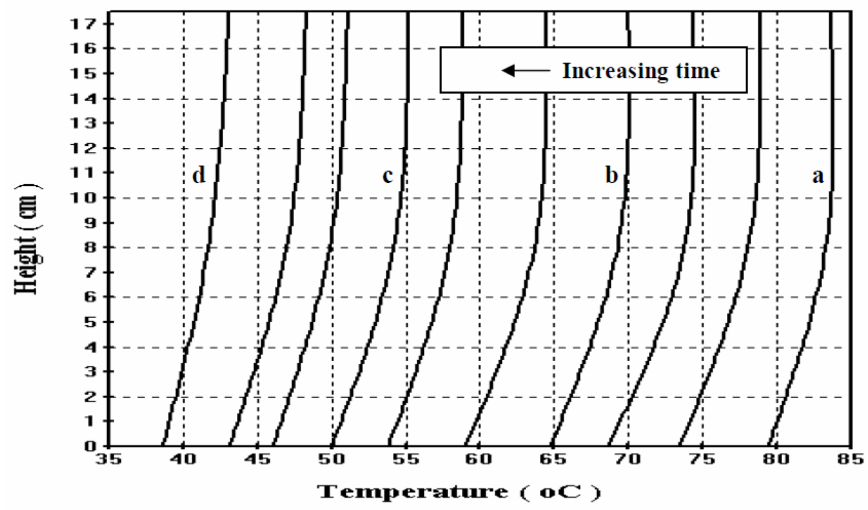

Figure-5. Distribution of average temperature with the tank height for aspect ratio ½.

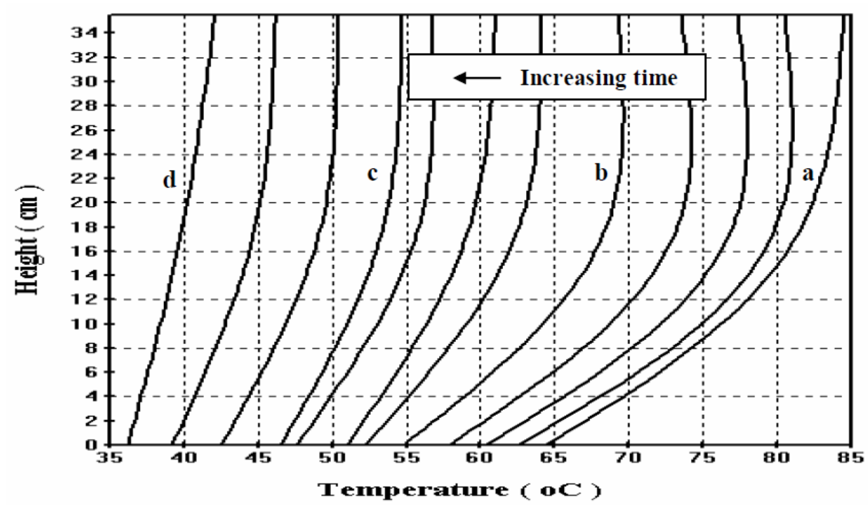

Figure-6. Distribution of average temperature with the tank height for aspect ratio 1.

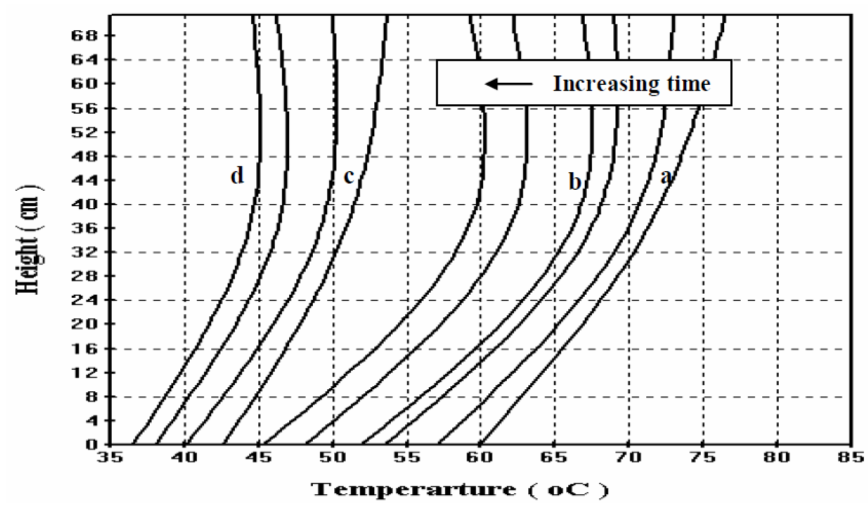

Figure-7. Distribution of average temperature with the tank height for aspect ratio 2.

4. CONCLUSIONS

The following conclusions may be drawn from the experimental study:

- As the tank with AR=½ loses more heat to the surroundings, the top half of the tank becomes slightly more stratified with time while the stratification at the bottom half remains almost unchanged with a steady temperature difference of around 5°C between the top and bottom;
- For the tank with AR=1, the stratification in a small part at the top was weak while that in the rest of the tank was clearly visible and gradually destroyed with time. The temperature difference between the top and bottom of the tank is reduced gradually with time from around 20°C to 5°C;
- The stratification in the tank with AR = 2 was clear in the whole tank. As the tank loses more heat to the surroundings, the stratification in the upper on third of the tank loss stratification gradually while the rest of the tank becomes progressively less stratified;
- The above points indicate that the heat loss to the ambient is a major factor in degradation of the thermal stratification in an un-insulated tank;
- The stratification was found to decrease continuously during the cooling period; and
- A better thermal stratification is achieved by increasing the aspect ratio.

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