Study of stratification in a (ICSSWH) Integrated Collector Storage Solar Water Heater

H.A. Junaidi* and D. Henderson†;
Napier University, Edinburgh UK, EH11 1HF

T. Muneer ‡
Napier University, Edinburgh UK, EH11 1HF

T. Grassie§; J. Currie**
Napier University, Edinburgh UK, EH11 1HF

Stratification inside the water storage tank of a solar heater is a desirable natural phenomenon that improves the collector output. For an ICS storage heater type, where the storage tank is in direct contact with the heating surface (absorber plate), stratification becomes more important as it plays an additional role of defining the heat gain characteristics. In the present research, stratification has been studied for a simple flat plate integrated collector storage (ICS) type heater at various inclinations and applied heat flux values. Experimental results have been compared to CFD results and good agreement is found between the two. The influence of stratification on the heat gain characteristics has also been examined. As the collector can be mounted at different angles to maximize solar gain at different latitudes, the angle of inclination of the solar water heater can vary in range 0°-90°. This variation in angle influences the stratification pattern. The study of stratification is important for determining the weighted average temperature, which is the sole parameter to evaluate the total heat gained by the water inside heater. It was found that stratification changes with the change in the angle, applied heat flux and time. These changes were experimentally recorded and analyzed to evaluate the thermal response of the system to the stratification. CFD studies were also carried out for deeper insight as the experimental setup did not provide finer details. The results can be used for designing outlets for ICS heaters at various locations.

Nomenclature

d	=	Depth (m)
T_x	=	Longitudinal temperature
T_x/T_{max}	=	Dimensionless temperature
L	=	Height of vertical storage tank
D	=	Diameter of vertical storage tank
Φ	=	Angle of inclination of collector

* Research Student; School of Engineering; Napier University, 10 Colinton Road, EH 10 5DT
† Director of Studies, School of Engineering; Napier University, 10 Colinton Road, EH 10 5DT
‡ Director of Research, School of Engineering; Napier University, 10 Colinton Road, EH 10 5DT
§ Lecturer, School of Engineering; Napier University, 10 Colinton Road, EH 10 5DT
** Lecturer, School of Built Environment; Napier University, 10 Colinton Road, EH 10 5DT

I. Introduction

Stratification inside the water storage tank primarily determines the useful heat output of the SWH. Numerous studies have been conducted on stratification in detached vertical storage tanks of solar water systems. For integrated collector storage types of SWH, which functionally is an absorber and storage unit in one, no evidence (to the authors knowledge) of any detailed study on stratification was available. The heater in consideration is the simplest type of heater i.e. the rectangular storage ICS heater (also referred to as batch heater) as illustrated in fig.1. The mentioned heater can be inclined to an angular range of 0˚-90˚ (φ). The inclination used depends mainly upon the geographical location (latitude) and incorporation of a seasonal collection bias in the tilt (up to ± 20˚) for summer or winter season. The inclination of the water heater induces variation in the stratification profile (temperature variation along the longitudinal length of the heater). This variation can considerably alter the heat gain and loss characteristics of the heater with passage of time. To estimate the total useful heat content of the heater at any time, and consequently evaluate performance of the heater, acquisition of these temperature profiles are essential.

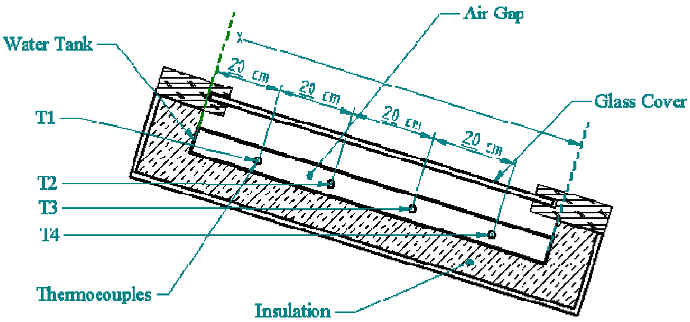

Figure 1, Rectangular storage ICS collector; the location of thermocouples is also shown.

Previous research on stratification inside storage tanks has been segmented into static and dynamic modes. The static mode is limited to the study of temperatures for fully or partially charged heaters with time, while the dynamic mode deals with charging and discharging cycles. The present article deals only with the static mode of operation. The effects of draw-off have been left out for the sake of brevity. Stratification for rectangular storage ICS heaters at various inclinations has been investigated thoroughly. The results can be applied to other similar variants of ICS type heaters. The present article is the outcome of research carried out for the development of an optimal solar water heater attuned to Scottish conditions.

II. Stratification in ICS heaters, an overview:

The importance of stratification over the useful energy collection has been highlighted by several authors [1,2,3,4]. The dependence of stratification on system temperature, storage tank dimensions (aspect ratios), baffle plates, dimension and location of the inlet and outlet ports, porous outlet manifold and the flow rates have also been studied extensively [4,5,6].

Thermal mixing that occurs when cold water enters the tank is detrimental to stratification as it stirs an entropy increase and thus the drop in the overall energy yield. Similarly night time losses- which are a major draw back in such heaters- can be curbed by segregating hot and cold water. This renders the knowledge of stratification crucial to the design in any solar water heating system. Many variations of designs that minimize mixing and effectively utilize

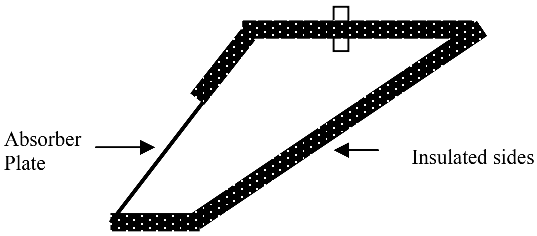

Figure 2, Trapezoidal heater by Cruz et al [7] for Portuguese conditions

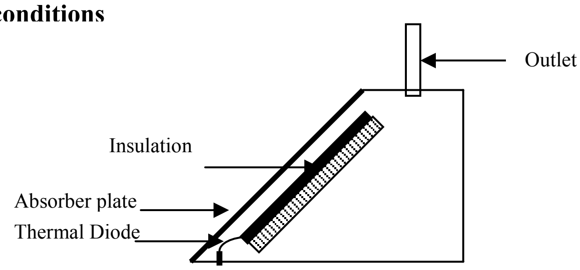

Figure 3. Schematic diagram of ICS heater by Mohammad [8]

the hot water accumulated at the top have therefore evolved. A trapezoidal heater by Cruz [7] was developed for Portuguese conditions on the basis that a trapezoid cross-section induces stratification and provides greater storage capacity for hot fluid at the top. Fig. 2 illustrates the shape of this heater. The noteworthy feature of the heater is that unlike other ICS types only a portion of the surface facing the sun has been used as absorber plate and the rest covered by insulation. While the authors have not established a substantial reason for this geometrical modification, it can be attributed to the prevention of night time losses from the hot water which remains confined by three insulated sides. Likewise another unique heater shape has been suggested by Mohammad et al [8] (Fig.3), which incorporates the use of a thermal diode. Clear evidence of thermal stratification was observed. Although experimental measurements for variation of temperature along the height were not illustrated, his numerical calculations did account for stratification inside the tank. Garg and Rani [9] used a baffle plate to suppress the night time losses (Fig.4). They found the collector performance to improve by 70%. The use of baffle plate improved the performance during the day as well as the night time. The baffle plate creates a channel that aids directing of the convective flow.

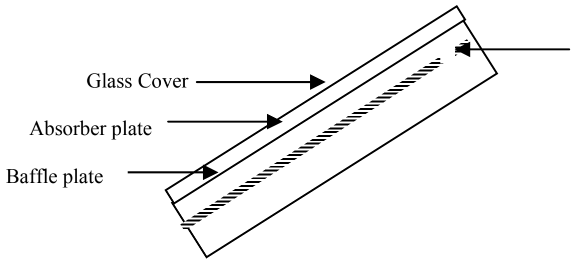

Figure 4, Schematic diagram of heater by Garg and Rani [9]

The present study deals with a collector very similar to the one proposed by Garg et al. Rectangular storage tanks are also a part of the more recent heater design proposed by Liu et al [10]. The tested heater has a simple configuration consists of a rectangular water storage tank with dimensions 1m x 1m x 0.05m (aspect ratio 20:20:1) framed inside a wooden box with a glass cover on top. Glass wool fills the gap between the tank and wooden box wall. The depth of the storage tank was set attuned to Scottish conditions and was deduced in light of earlier studies by Muneer et al on similar heaters [11-13]. During the operation mode of the collector, the onset of insolation initiates heating up of the absorber plate. This results in the development of a thermal, and consequently a velocity boundary layer (BL) on the inner (water) side of the absorber plate. Rising fluid gets further heated as it moves along the absorber plate. Hot water accumulates at the top and slowly starts diffusing into the bottom, cooler layers of fluid. The rate of heat transfer increases initially with the development of velocity BL until it reaches a peak value whereon it gradually declines owing to increasing stagnant fluid region at the top and increased system temperature. The greater the angle (0˚-90˚) the higher the Rayleigh number and thus higher the rate of initial heat transfer. The waterside heat transfer coefficient is gradually affected due to the accumulation of hot water beneath the absorber plate at the top portion of the tank. The absorber plate in such heaters has highly non-uniform temperatures. Therefore calculations for heat gain/loss by established methods of flat plate tube type collectors are not appropriate as the air gap between the cover and absorber plate doesn't lend itself to be treated merely as an inclined natural convection cavity. To work out heater characteristics it is imperative to know the absorber plate temperature which is strongly coupled to the temperature of the water beneath it.

III. Apparatus and Procedure:

A full scale collector was fabricated and tested in the laboratory under controlled conditions. A resistance heating pad was used for imposing heat flux while 16 K-type thermocouples measured the system temperatures at various positions (Fig.1 also illustrates the position of thermocouples along the longitudinal length of the heater). CFD analysis was carried out using Fluent 6.2 code. The geometry was meshed with structured quadratic elements. Boussinesq approach was used to model the density, while QUICK scheme

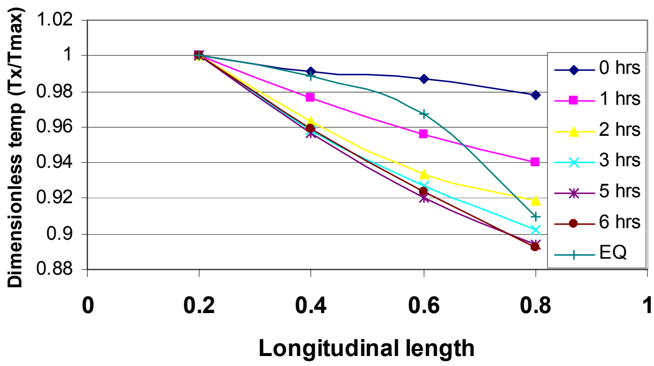

Figure 5, Dimensionless temperatures along the longitudinal length for φ= 30˚, 100W

was used as the discretization scheme. Transient analysis was carried out for angles 30˚, 45˚, and 60˚ for first 20 minutes.

The experimental results (temperatures at four positions along the longitudinal length "x") for applied heat flux values of 100 and 200W and for angles 30˚, 45˚, and 60˚ are shown in figures 5-10 respectively.

IV. Results

Dimensionless temperatures have been plotted on hourly basis for the first five hours of charging time. In addition, the stratification profile for the system reaching equilibrium (i.e. when all imposed heat flux goes into losses) has also been plotted (curves denoted by "EQ" on the plots). For an un-stratified tank, the degree of stratification is seen to increase initially (increasing slope of curves) with time and temperature profile shows a concave curvature. This trend gradually changes and proceeds towards a bulging contour. A convex

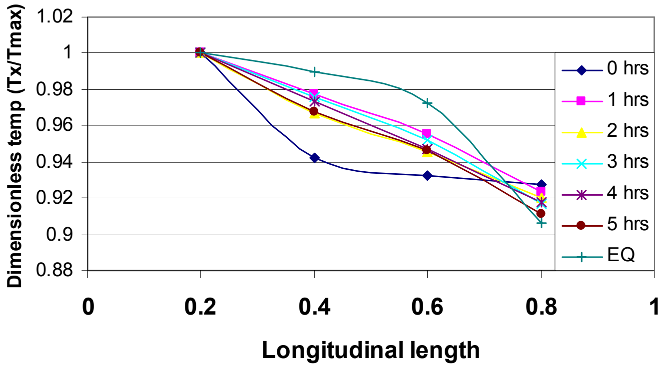

Figure 6, Dimensionless temperatures along the longitudinal length for φ= 45˚, 100W

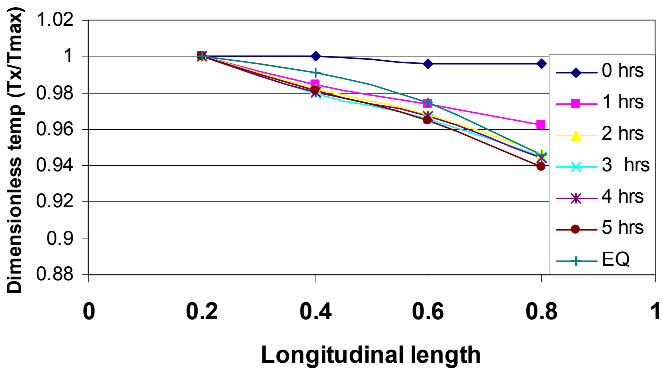

Figure 7, Dimensionless temperatures along the longitudinal length for φ= 60˚, 100W

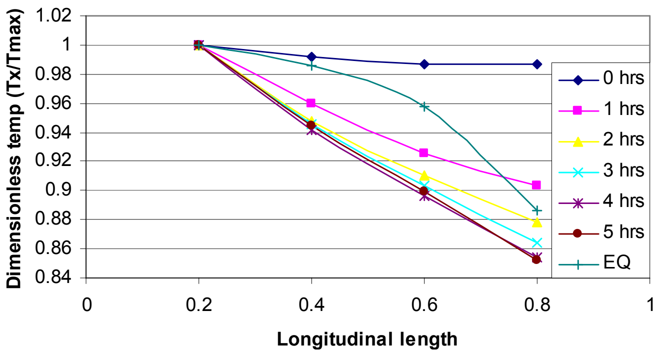

Figure 8, Dimensionless temperatures along the longitudinal length for φ= 30˚, 200W

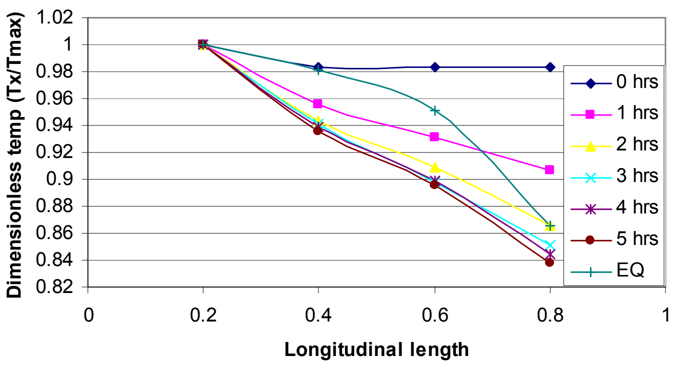

Figure 9, Dimensionless temperatures along the longitudinal length for φ= 45˚, 200W

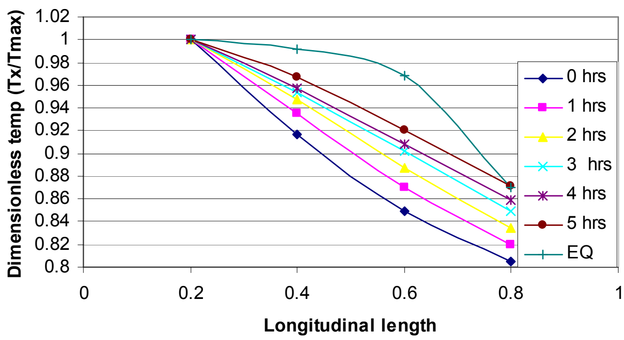

Figure 10, Dimensionless temperatures along the longitudinal length for φ = 60˚, 200W

profile is noticed for the system reaching equilibrium for each case. As anticipated, it can also be noticed that stratification increases with the increase of heat flux. The convex profile inside however is trivial as in all cases it was reached after a charge period of 12 hours, which for SWH is of slight practical value owing to shorter discharge cycle periods. At the angle 30˚, the minimum and the maximum temperatures show a greater difference as compared to 45˚ or 60˚. It is also interesting to note here that for 60˚ at 200W (fig.10) the tank was highly stratified at the beginning. The imposed flux in this case directly went into changing the temperature profile to a convex profile. This implies stratification profile is additionally dependent upon the initial stratification inside the tank.

From CFD analysis it is evident that for the first 10 minutes the bottom thermocouple (T4) should depict a slight change in the temperature compared to the top (T1) as heated water will rise and accumulate at the top of the tank and would subsequently diffuse into bottom part of the heater. Initially convective currents play a predominant role in heating up the inside fluid, however later on diffusion becomes dominant.

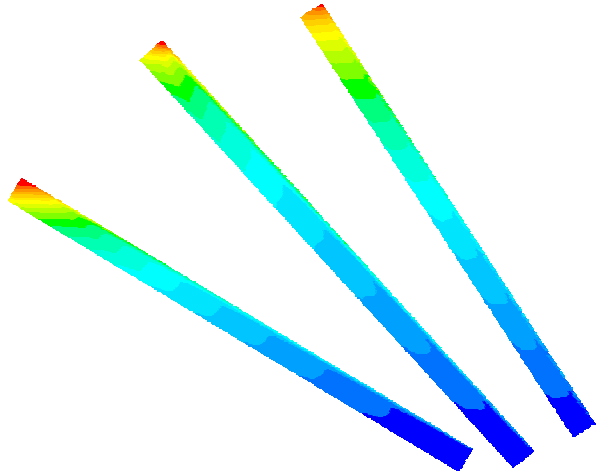

Figure 11, Shows the temperature contours from CFD for φ = 30˚, 45˚ and 60˚

Fig.12 shows the CFD results for temperature profile along the middle plane of the heater for the 100 W after the first 20 minutes. The analysis was carried out with the tank initially being isothermal. The concave profile established through experiments is apparent.

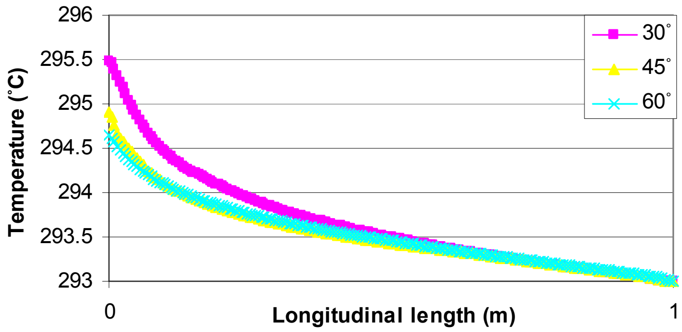

Figure 12, Temperature profile along the longitudinal length at the middle plane through CFD analysis for φ = 30˚, 45˚ and 60˚ after 20 min

V. Effect of depth of the storage tank:

The depth of the storage tank also effects the stratification inside storage tanks. In contrast to stratification in a vertical storage tank - where the temperature gradient exists only along the vertical direction- the ICCS storage tank carries the gradient along both the longitudinal and the lateral directions due to its angular placement. Through CFD analysis, it was found that a temperature difference of 0.8˚C at the top and 0.4 ˚C at the bottom existed for the heater. As the depth of the tank was merely "50mm", a significant variation in temperature wasn't recorded. Fig.13 and 14 highlight the stratification along the depth for different angles (30˚, 45˚ and 60˚) and sections (bottom, middle and top) respectively.

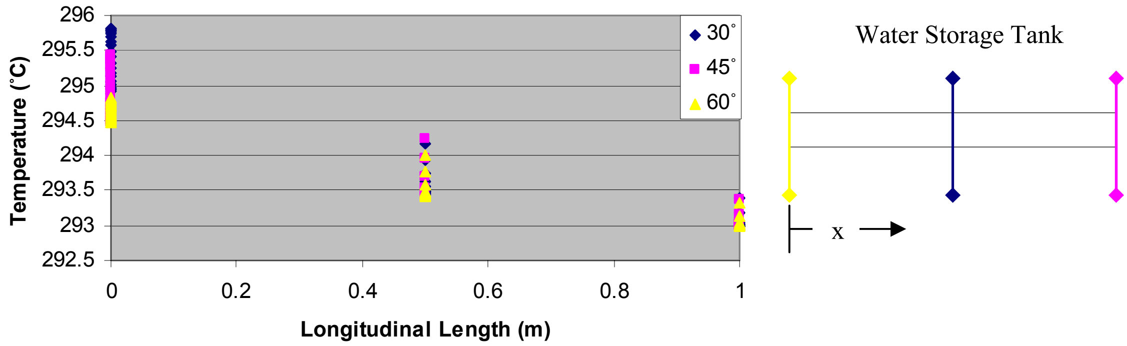

Figure13, Temperatures along the depth of the heater at three segments

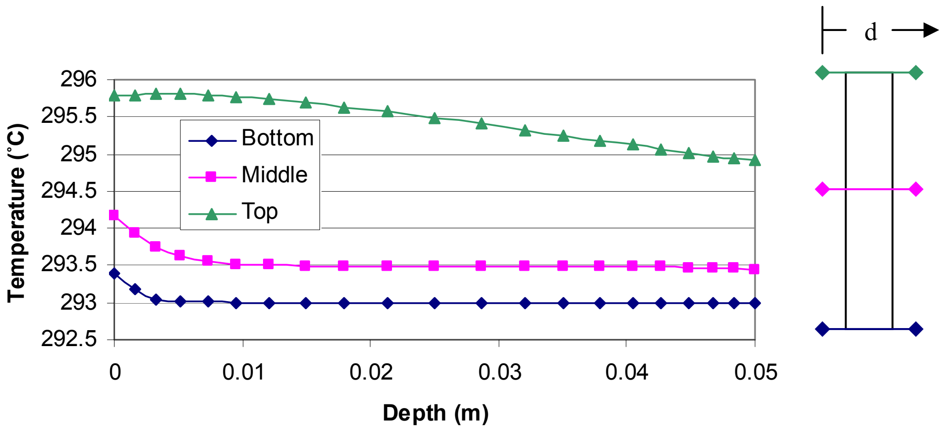

Figure 14, Temperature along the depth of the heater at three segments

Compared to detached storage tanks, where the magnitude of convection activity may come nearly to a halt and the process would become quasi steady state when the difference between the draw-off intervals is high, the process of stratification and current remains transiently dynamic in a batch heater as long as it is exposed to insolation.

VI. Stratification with change in angle

Previous studies have illustrated stratification dependence on the aspect ratio of the storage tanks. Lavan and Thompson [1] suggest that improving the "L/D" and "ΔT" in a cylindrical detached storage tank improves stratification. Where "L" is the height and "D" is the diameter of the cylinder and "ΔT" is the temperature between inlet and outlet. For the rectangular storage, it is apparent that lower angles of inclinations result is smaller aspect ratio of the vessel and thus undermine stratification. Higher angles on the other hand aid stratification. In an ICS however although the increasing angle of inclination increases the aspect ratio which would aid stratification however natural convection that is also coupled to the angle compounds the temperature accumulation at the top. It was noticed through both CFD and experimental results that a higher degree of stratification exists for 30˚ for 100W. The trend is seen to change for increased heat flux values. Recent studies have indicated that a volume average approach is being used with very few numbers of thermocouples to calculate the energy content. CFD results indicate the steep temperature gradient at the top and the bottom of the heater. The temperature in the middle of the heater is fairly stable showing a gradual declination. In a recent article by Liu et al [6], an increase in stratification with increasing heat flux has been noticed.

VII. Conclusions

Through experiments and CFD analysis it was ascertained that stratification inside the storage tank of ICSSWH is influenced by several factors. These include the dimensions of the rectangular vessel, the angle of inclination, exposed solar radiation, the time of exposure as well as initial degree of stratification of the water inside the tank. The thermal and the velocity boundary layers on the inner side of the absorber plate enhance stratification. The heat losses from the top portion of the tank increase with the passage of time owing to the accumulation of hot

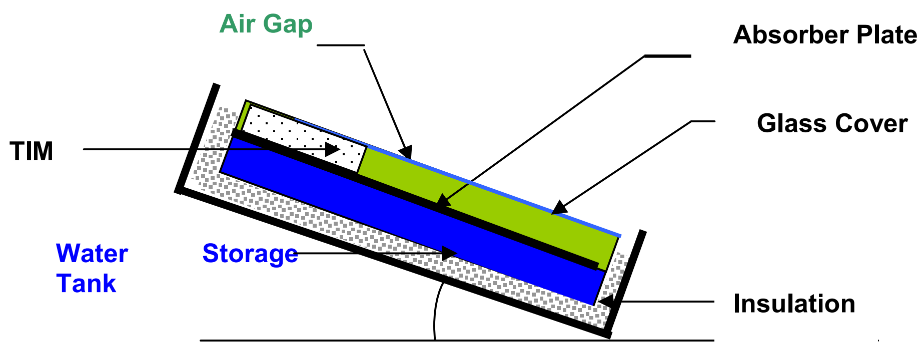

Figure15, Visual depiction of the suggested usage of TIM

fluid. Higher degree of stratification was noticed with increasing heat flux values imposed on the collector. A concave temperature profile was attained by the system initially. With the passage of time the profile became linear and finally convex at equilibrium. In light of these results, it is suggested that the top portion of the water tank should be insulated to a higher degree as compared to the bottom portion. To further curb the heat losses from the top section, a calculated segment above the absorber plate (the air gap) can be packed by insulation as shown in fig.15. A fitting solution for this insulation purposes would be the use of TIM [Transparent Insulation Material]. The usage of TIM to pack the entire air-cavity would be costly. In additional to that it also reduces the optical efficiency of the heater due to transmission losses. A calculated size of TIM depending mainly upon the angle can significantly lower the heat losses as well as reduce material cost. TIM would serve a dual purpose; not only will it promote stratification but will also prevent heat loss in the night time as it will increase the thermal resistance between hotter fluid and the ambient.

Acknowledgements

The authors are thankful to Ms. Celine Garnier for allowing us the use of the collector data for modeling purposes.

REFERENCES

1. van Koppen, C.W.J., Thomas, J.P.S. and Veltkamp, W.B. (1979). The actual benefits of thermally stratified storage in a small and medium size solar system. Proceedings of ISES Solar World Congress, 1979, Atlanta U.S.A. pp 579-580.

2. Furbo, S. and Mikkelsen, S.E. (1987). Is low flow operation an advantage for solar heating system? Proceedings of ISES Solar world congress, 1987, Hamburg, volume 1, pp.97-105.

3. J.Van Berkel; Mixing in thermally stratified energy stores; Solar energy, vol. 58, No 4-6, pp-203-211, 1996.

4. Zalman Lavan and James Thompson; Experimental study of thermally stratified hot water storage tanks; Solar Energy Vol. 19, 519-524 .

5. Necdet Altuntop, Mevlut Arslan, Veysel Ozceyhan, Mehmet Kanoglu "Effect of obstacles on thermal stratification in hot water storage tanks". Applied Thermal Engineering 25 (2005) 2285-2298.

6. N. Gopalakrishnan, B.V.S.S.S.S. Prasad, S. Srinivasa Murthy; "Natural Convection in Stratified Hot Water Storage Tanks", Rio 5- World Climate & Energy Event, 15-17 February 2005, Rio de Janerio, Brazil.

7. Jose´ M.S. Cruz, Geoffrey P. Hammond, Albino J.P.S. Reis "Thermal performance of a trapezoidal-shaped solar collector/ energy store", Applied Energy; 73 (2002) 195–212.

8. A.A. Mohamad; Integrated Solar Collector-Storage tank System with thermal diode; Solar Energy, Vol. 61, pp. 221-218, 1997.

9. H.P. Garg and Usha Rani; "Theoretical and Experimental Studies on Collector/ Storage Type Solar Water Heater" Solar Energy Vol. 29, No.6 pp. 467-478, 1982.

10. W. Liu; J.H. Davidson; F.A. Kulacki; "Characterization of Prototypical Integral Collector Storage Systems With Immersed Heat Exchangers"; Journal of Solar Energy Engineering.

11. T. Muneer, Effect of design parameters on performance of built-in storage solar water heater; Energy conservation and Management Vol. 25, No. 3, pp. 277-281, 1985.

12. T. Muneer, M.M. Hawas; Experimental study of the thermosyphonic and built-in storage type solar water heaters; Energex 84 conf. Regina, Canada, June 1984.

13. T. Muneer, S. Maubleu and M. Asif; "Prospects of solar water heating for textile industry in Pakistan"; Renewable and Sustainable Energy Reviews, Vol 10, issue 1, February 2006.

14. Wu, L and Bannerot, R.B., 1987" Experimental study of the effect of water extraction on Thermal Stratification in Storage," Proceedings, 1987 ASME-JSME-JSES Solar Energy Conference, Honolulu, Vol, pp. 445-451.