Solar hot water installation with stratified accumulation

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Abstract: Domestic solar hot water systems perform more efficiently if they use thermally stratified accumulation. A special system for investigation of thermal stratification accumulators was built in South-West University in Bulgaria in 2002. This system presents possibilities to work in different regimes of thermal accumulation and climatic conditions. The experimental apparatus allow working in direct or indirect configuration of installation. Many experiments were performed to specify the optimal regime's parameters of installation. The results of the studies show that by appropriate choice of the parameters, efficiency of the installation can be improved considerably. A computational model and computer program for heat exchange process in accumulation tank was created. The theoretical model was verified with experimental data. A good correspondence between theoretical and experimental results was achieved.

1. Introduction

Thermally stratified storage tanks for solar hot water installations have been widely used in domestic sector in the last years. In such systems the hot water remains separated from the cold water by means of buoyancy forces. Stratified storage tanks are more thermally and economically effective. Maintaining thermal stratification is very important. This ensures that solar collectors work with maximal thermal efficiency. It is because the inflow to the collector is taken from the bottom of a stratified tank (the coldest layer in tank). On the other hand, hot water for consummators is charged from the top of accumulator, where the highest water temperature is kept. This delivers useful energy on demand.

Degradation of thermal stratification in storage tanks is caused by different thermal mechanisms (Zurigat et al.,1989; Shahab A., 1999). The first mechanism is the forced convection flow through the tank. Inflow and outflow streams in tank during the charging process and momentum-induced mixing between the incoming and resident water are a major cause of destratification.

The next reason can be the natural convection caused by receiving a colder fluid from solar collectors in the top of thermal accumulator, where is the highest temperature layer. This depends on the weather conditions (clouds) and the fluid flow rate in collector circuit. If the flow rate in collectors is high, a small temperature increase is performed in collectors and possibility to receive a cold convective stream in the top of the tank is more realistic. On the other hand, the high flow rate in collector circuit (for direct solar installation) leads to short cycle of full water passing through the collectors and small temperature difference in stratified accumulator.

The other thermal mechanisms are the heat loss to the ambient, thermal mixing at the inlet and outlet, natural convective flow induced by conduction within the walls and heat diffusion inside the tank due to the vertical temperature gradient in the fluid.

A variety of models and experiments to assess the efficiency of stratified tanks have been produced. As a result many numerical and experimental studies have been conducted on the performance of stratified tanks under different operating conditions and constructive parameters. The most of published studies analyze the direct solar installations or indirect installation with removed heat exchanger, where mass and thermal transport mechanism in accumulator and heat exchanger are separated. If an indirect solar installation with serpentine (included heat exchanger) is used, the thermal exchange and accumulation perform simultaneously at some place. Such installations are often used as domestic hot water suppliers for solar energy utilization.

Solar installations with stratified tanks and heat exchange by included serpentine have advantages, because the destratification by fluid mixing in charge phase is eliminated. Only in discharge process the fluid mixing is available, but with some constructive measures the losses in stratification can be minimized. Moreover, the place of heat transfer in tanks can be regulated with serpentine disposition. The serpentine can be situated in upper, middle or bottom part of the tank. What is the right position of the heat exchanger (serpentine) is a disputable question. It depends on many factors and studies in this field will help designers and constructors on solar installations for hot water.

Motivated by this point, the present study is intended to investigate performance of typical domestic hot water installation in different regimes of thermal accumulation and climatic conditions. In order to wide scope for investments, a computational model and computer program for heat exchange process in accumulation tank was created. Many experimental and numerical studies have been conducted on the performance of stratified storage tank under different operating conditions and for different design characteristics. These characteristic include the parameters and situation on the heat exchange serpentine, flow rate in collector circuit, water consuming regime and other.

2. **Experimental apparatus and measure instruments**.

The solar system is installed on the flat roof of South-West University “N. Rilski” (SWU) – Blagoevgrad. The coordinates of the solar complex are latitude - $42^0$1’34’’N, longitude - $23^0$5’51’’ and altitude – 350 m. The design and realization of the system were oriented to simulate different regimes of solar energy conversion and hot water consumption. The main target is to ensure possibility to: work in direct and indirect regime with different heat exchange area and location of serpentine unit in tank; change angle of collectors toward by horizon and azimuth; regulate some operating parameters (fluid flow rate); measure all important parameters, influence the system performance.

A schematic diagram of the solar installation and the test apparatus is shown in Fig.1. The test tank is a vertical cylindrical tank made of stainless steal material. The tank height is 1.7 m with an internal diameter of 0.35 m. The volume of the tank is 160 l, which is a typical water capacity for a family house. At the top of the tank there is an outlet fitting for water consuming. Other fitting is located at the bottom of the tank and it allows injection cold water from water supply net. The tank and connection pipes are well insulated.

In the tank are built in three copper serpentines along in all the height of the tank. Serpentines are 10 meters each in length. They can be switched on or off as a heat exchange unit by system of valves. So the system can work with one, two or three serpentines situated in different regions of the tank. Installation can work also in direct regime, when all three serpentines are turned off.

The system is equipped with flat solar collector 2 m^2 in area. The mechanical construction allow five discrete points to fix angles toward by horizon by 30, 40,42,45,50 grad. The system is equipped with expansion vessel, pump, valves and other additional elements.

Monitoring system includes 12 thermo sensors assembled in accumulation vessel, 6 thermo sensors in collector circle and one thermo sensor for a measuring the ambient air temperature. Solar meter, located near the solar collectors measures solar radiation. The inflow rate, heat energy and heat power are measured by combined heat-meter. All observed parameters are registered by automatic monitoring system. It includes a special electronic module for converting the analog data from sensors to digital signals. Digital data from converting module is collected by computer system. After that, stored data can be used for detailed analysis of thermal and economical efficiency of system and preparing the statistical calculation for long-term analysis.

Measuring module includes also a control unit, which governs the pump performance. It starts pump, if the temperature difference between inlet and outlet temperature of working fluid is above preliminary defined value. Ordinarily, the systems work stable and efficiently with control temperature difference between 2 and 5^{o}C.

Consumption of hot water is realized by simulation of a typical consumption regime for small restaurant hot water system and domestic (family) hot water system.

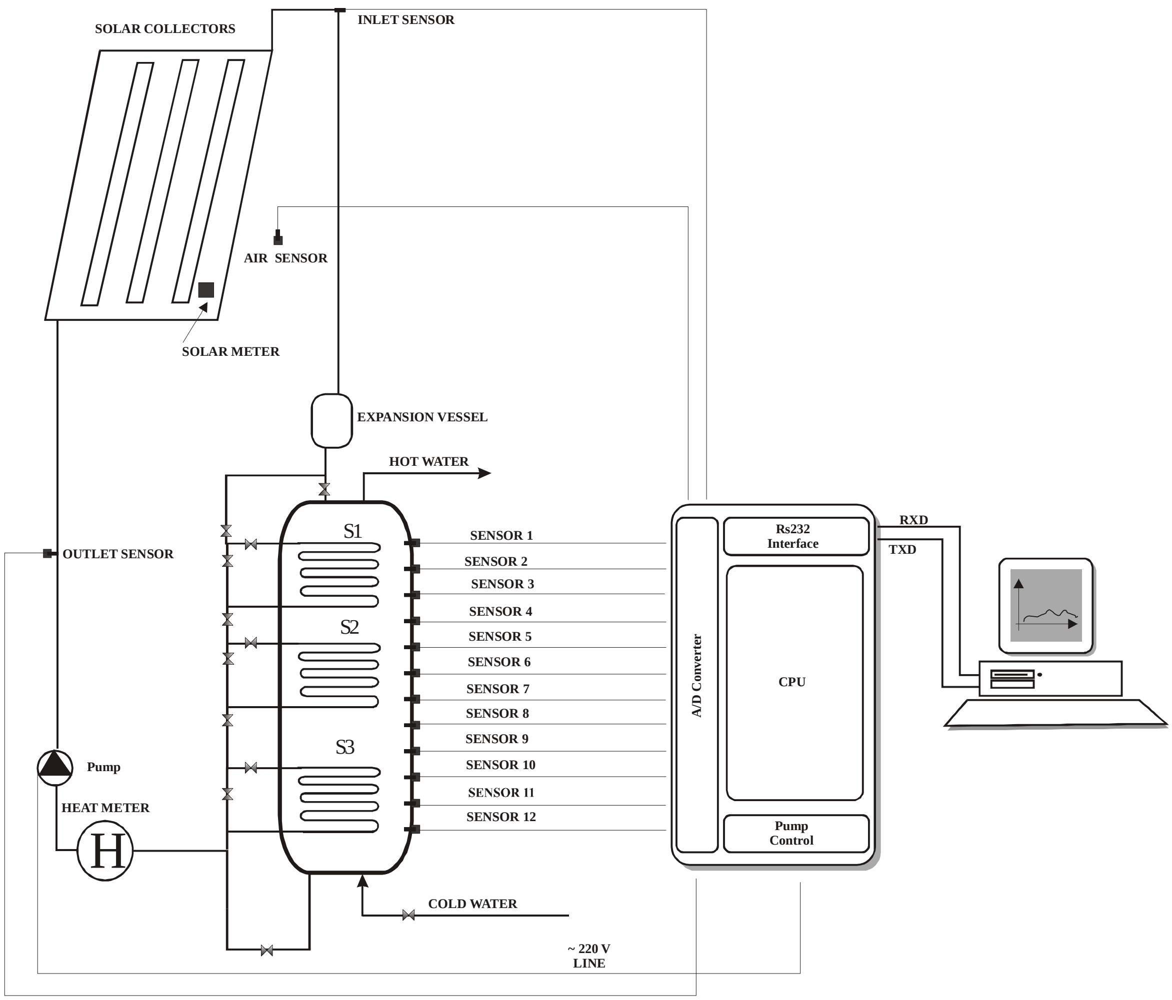

FIG.1 Schematic diagram of the test apparatus

3. Theoretical modeling

Numerical modeling of thermal storage tanks is often used technique to investigate thermal and mass processes. Although two or three-dimensional analysis are possible to describe flow and temperature distribution in storage tank, they are not applicable to simulation calculations of the long-term performance due to insuperable difficulties of calculation algorithms. This is especially true for the transient behavior of the tank performance. Hence, one-dimensional modeling is possible alternative, because of its simplicity and sufficient accuracy of computational procedures (Hoseon Y et al. 1999)

In the present study a simple one-dimensional numerical model have been developed for predicting the transient behavior of the vertical temperature distribution in tank. The model describes temperature changing in different layers of the tank by means of momentary energy balance for defined quantity of water.

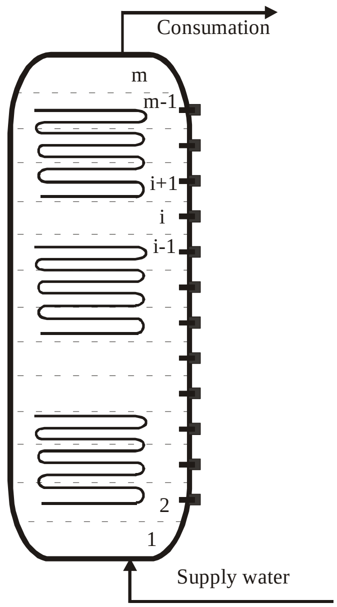

Fig.2. Schematic diagram of the tank

The stratified accumulator considered in this study is divided into ***m*** sectors (corresponding to the number of thermo sensors) with the equal volume, as depicted schematically in Fig.2. The sectors are numbered from the bottom to the top of tank. Different sectors contain different parts of heater (serpentine). This means that in sectors act different heat sources (heat exchange area). The intensity of heat, transferred by serpentine to the water in tank, decreases from up to down, because the temperature of working fluid is decreasing by heat extracting.

Hot water is consuming from upper sector of the tank. Consumed water quantity is compensating by injection cold water at the bottom sector. This water is assumed to mix with the water in the sector. Some quantity of water from bottom (1) sector enters the next upper sector (2) and mixes with water in the sector. This process occurs in all next sectors of the tank. The temperature changes in sectors by discharging process can be written by:

$$T_{i,n} = \left[(V_i - \nabla V)T_{i,n-1} + \nabla V T_{i-1,n-1}\right]/V_i \,,$$

where ***i,n*** are sector and time step number; ***V*** is volume and **T** - temperature of water. ΔV is quantity (volume) of consumed water for time step ***n***. For the bottom sector (1) the temperature $T_{i-1,n-1}$ is the net supply water temperature T_{net}. Discharging process is simulated by sequent passing the sectors from the bottom to the top.

In the same time, another process is taking place - the thermal charging process. The heat from solar collectors is transferred to the water in tank by serpentine elements. This causes temperature rise in tank. Temperature rise depends on the outlet temperature from solar collectors and flow rate of the working fluid. The charging process can be considered as independent (superposition principle). Hence, a second passing across the sectors for the same time step is needed to determine the temperature rising. Energy balance in sectors gives the temperature change:

$$T_{i,n} = T_{i,n}' + \frac{K_{i,ser}F_{i,ser}}{\rho V_i c_p}(T_f - T_{i,n}')\nabla\tau \,,$$

where $T_{i,n}'$ is temperature in ***i***-sector and ***n***-time step, after the discharging process has passed; T_f - average fluid temperature in ***i***-serpentine element; $\Delta\tau$ - time step interval for charging process; $K_{i,serp}$ and $F_{i,serp}$ - heat transfer coefficient and heat exchange area of serpentine element for ***i***-sector; ρ and c_p - density and specific heat capacitance of water in tank.

Calculations of charging process is made in reverse direction - from the top to the bottom of tank. This is because the direction of working fluid in serpentine is from upper elements to the lower ones. Average temperature of working fluid T_f is: $T_f = (T_{in}+T_{out})/2$, where T_{in} and T_{out} are inlet and outlet temperature of working fluid in serpentine element. Inlet fluid temperature T_{in} in ***i***-sector is the outlet temperature from the previous (upper) serpentine element (sector $i+1$). The outlet temperature T_{out} depends on transferred heat energy in a sector. As the transferred energy depends on average fluid temperature there is an indetermination in sequenced equation, a special iteration procedure was used to calculate needed temperatures.

For the upper sector inlet fluid temperature in serpentine element is determined by solar collector's performance. Mathematical model for solar collectors is well-established matter and can be found in solar energy publications (Duffie J.,W. Beckman, 1980). Special simulation algorithm binds the collector and accumulator models in a working unit. Computer program is created to manage the theoretical calculations.

In this model, the thermal diffusion within the tank has been neglected. Because of good insulation of the tank and pipes losses to ambient was not considered.

4. Experimental results and model validation

In order to validate the presented model and to analyze performance of solar installation with stratified accumulation numerous experiments and calculations have been made. After a thorough investigation, appropriate values and formulas for parameters in mathematical equations and parameters of simulation calculation were chosen. A satisfactory coincidence between experimental and theoretical results was achieved. Since there are difficulties to arrange all initial parameters in mathematical system with real parameters for tank, solar collectors and climatic conditions, we assume that the correlation between the theoretical predications and measured data is good.

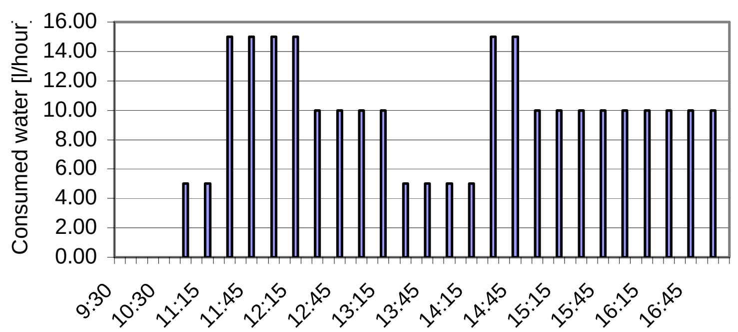

Fig.3. Distribution of consumed water

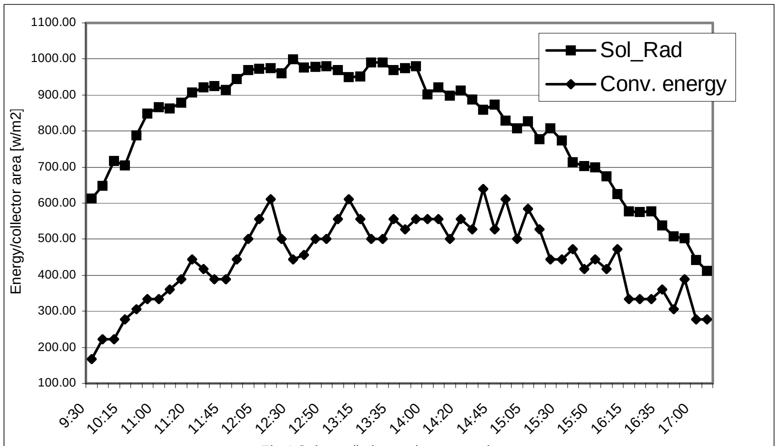

Fig.4 Solar radiation and conversed energy

In this study are presented and discussed some results related to the influence of serpentine location in tank on the system performance. All experiments are made in approximately equal conditions. Daily water consummation has a relatively regular distribution as it is shown in Fig.3. The water consumption is 200 l per day, which is water quantity, corresponding (or little smaller) to the collector area (2 m^2) possibilities for energy conversion. The solar radiation (fig. 4) has a typical summer distribution for Bulgaria latitude and varies for different experiments in very small range. Useful (utilized) energy has a typical daily distribution as it is shown in Fig.4. Variations in useful energy is caused by different inlet temperature for solar collectors.

Fig.5 shows the daily temperature distribution of water in tank for 6 sectors (layers). These results are addressed to system performance with two serpentines, located in top and bottom zone of the tank. Middle serpentine element is turned off. This is a thermally stratified accumulator because there is a top hot zone (sensors D12 and D11), middle temperature zone (sensors D8,D9,D10) and cold zone (sensors D1..D6). Lower half of tank is with cold water (30-35^{o}C) and small variation in temperatures. This is because there is a big quantity of water with relatively uniform temperature. The top zone is also with small temperature difference because it is constantly charged with heat by top serpentine. The most sensible to the water consumption is middle zone (sensors 8..10). Because the collector area is a bit smaller than what daily consumption require, the middle zone is situated in the upper half of the thank (D8..D10). On the other hand, cold zone is with relatively high temperature (30-35^{o}C) because there is a serpentine element heating the water in bottom zone.

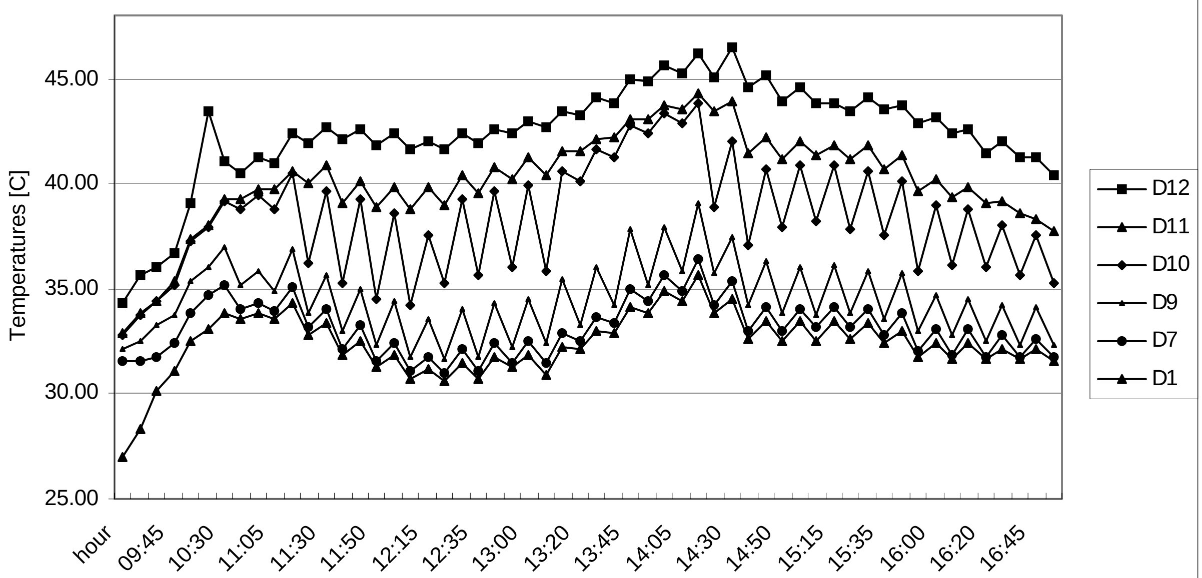

Fig.5 Temperatures in tank - two serpentines

Fig.6 shows temperatures from 6 sensors in solar installation with one serpentine configuration. The serpentine element is located at the bottom part of the tank. This is a configuration, which realize practically unstratified thermal accumulator. It is because the heat is extracted at the bottom and is transferred regularly to the top by buoyancy force. In this case the consumption is not so effective and the necessity of bigger collector area is evident. The thermal efficiency of this configuration is about 15% lower than configuration with two serpentines.

Fig.7 illustrate temperature distribution in different sectors of the tank for configuration with one serpentine located in the top zone. This is a typical stratified accumulator. The top zone is with high temperature (40-50^{o}C) and the bottom zone is with low temperature (25-30^{o}C). Difference with the case with two serpentines is that here hot and cold zones are clearly outlined and the cold zone is with lower temperature. Maximal temperature in the top zone is higher because the solar collectors work in higher temperature range (inlet collector temperature is determined by upper tank zone). This makes the thermal efficiency of solar collectors be lower than configuration with the two serpentines, but water consumption is with good efficiency.

Configuration with one serpentine at the top zone forms a big cold area in tank (sensors D1-D8), small middle (D9 and D10) and hot zone (D11 and D12). This is caused because the heat exchange area is small and big water quantity is isolated from heat exchange process.

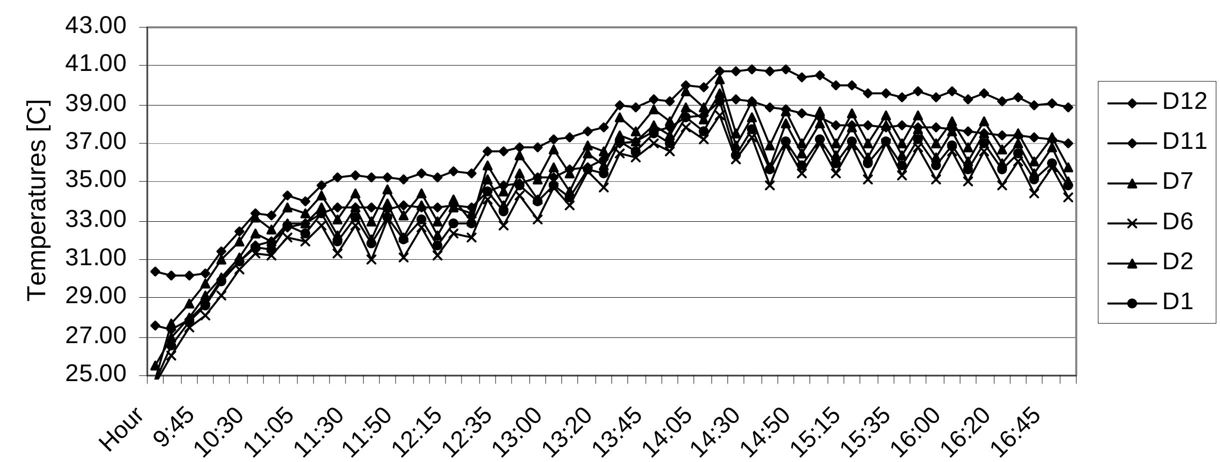

Fig.6. Temperatures in tank - serpentine in bottom

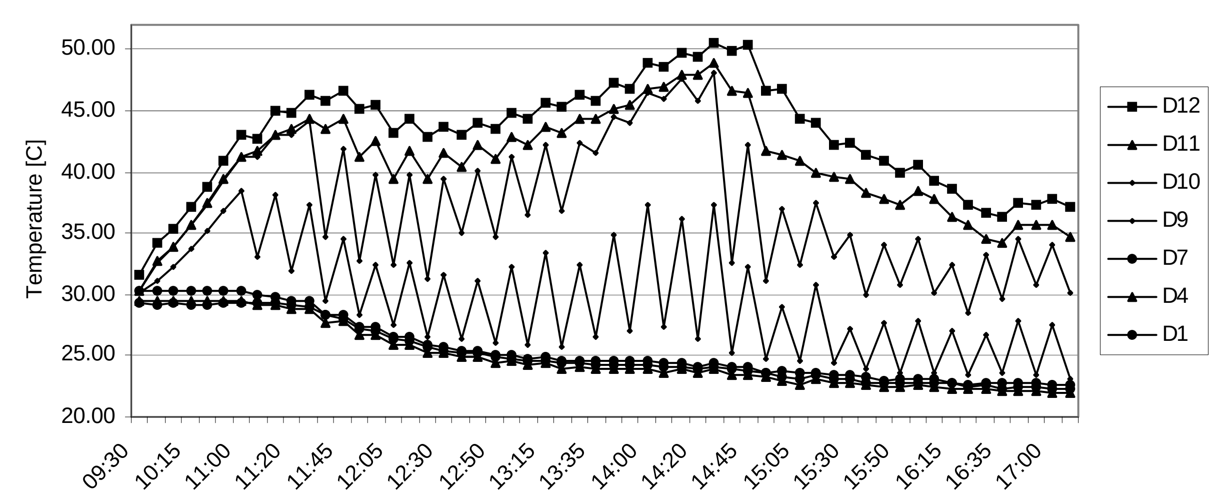

Fig.7 Temperature in tank - serpentine at top

Configuration with three serpentines has nearly the same efficiency as the configuration with two serpentines and here is not presented the results for it. Thermal efficiency is little higher, but it is not sufficient to compensate additional cost expenditure.

Presented results show the physical behavior of installation at special condition – daily-consumed water and distribution, climatic conditions, collector area and so on. At other conditions and parameters the behaviour will be other, but main results will resemble presented above.

5. Conclusions

The thermal stratification in domestic solar hot water systems has been investigated both experimentally and numerically. Special test module with monitoring system registers all needed parameters to analyse efficiency and physical behaviour of the system. Mathematical model for thermal accumulator was validated to wide investigation scope. The main purposes of experiments relate to investigate the influence of serpentine location in the tank on thermal performance of the system. Three different configuration of serpentine location have been investigated.

Serpentine location in bottom zone of the tank realizes unstratified thermal accumulation in solar installation. Thermal stratification can be arrived with serpentine location in the top zone of the tank. Results show that the stratification in tank improves thermal efficiency up to 15-20%. This can results in using smaller collector area to prepare hot water.

Thermal efficiency in solar installations is highest when thermal stratification is stable and it is formed with heat exchange in hot and cold zone. This ensures high thermal efficiency of solar collectors and delivers useful energy on demand.

References

1. J.A.Duffie and W.A. Beckman, *Solar engineering of thermal processes*, Wiley Interscience, New York, 1980.
2. G.F.Csordas, A.P. Brunger, K.G.T.Hollands and M.F. Lightstone, *Plume entraintment effects in solar domestic hot water systems employing wariable-flow-rate control strategies*, Solar Energy 49 (6), 497-505 (1992).
3. A. Shahab, *An experimental and numerical study of thermal stratification in a horizontal cylindrical solar storage tank*, Solar Energy 66 (6),409-421 (1999).
4. Y. Hoseon, C. J. Kim, C. W. Kim, Approximate analytical solutions for stratified thermal storage under variable inlet temperature, Solar Energy 66 (1) 47-56 (1999).
5. Zurigat et al., *A comparision study of one-dimensional models for stratified thermal storage tanks. ASME J. Solar Energy Eng.* 111, 205-210 (1989)