Thermal Accumulation in Solar Systems for Hot Water

Stanko Vl. Shtrakov, Anton Stoilov
South - West University "Neofit Rilski", Dept of Physics,
66 Ivan Mihailov Str., 2700 - Blagoevgrad, BULGARIA,
E-mail: sshtrakov@abv.bg, antonstoilov@abv.bg

Abstract - The major impediments for market penetration of solar hot water installations in Bulgaria are the lack of information and experienced data about the efficiency, thermal accumulation of energy and adequate exploitation in different seasons in a year and geographical regions. Defining useful recommendations for different regimes of exploitation, corresponding to the climatic conditions and installation parameters is the main purpose of this work. A special experimental solar module for hot water was built and equipped with sufficient measure apparatus. The main concept of investigation is to optimise the stratified regime of thermal accumulation and parameters of heat exchange equipment (heat serpentine in tank). Accumulation and heat exchange processes were investigated by theoretical end experimental means. Special mathematical model was composed to simulate the energy transfer in a stratified tank. Computer program was developed to solve mathematical equations for thermal accumulation and energy exchange. Experimental equipment with more than 15 temperature sensors and other measure devices gives data for the real processes. Extensive numerical and experimental tests were carried out. A good correspondence between theoretical and experimental data was arrived. Collected experimental and theoretical data from two years' exploitation period is a good base for establishing some important issues about construction and exploitation of solar installation with different consumption regimes. Analysis of collected data were used to make a detailed technical and economical assessment of hot water installations with respect to the climatic and economical conditions in Bulgaria. This data will help designers and investors to expand penetration of the solar energy application in Bulgaria.

1. Introduction

Solar hot water installations are the most often used solar applications in Bulgaria. The major impediments to further increase of the market penetration for these systems are the lack of information and experienced data about the efficiency, thermal accumulation of energy and adequate exploitation in different seasons in a year and geographical regions.

For small solar installations, used preliminarily in the domestic sector, the thermally stratified storage tanks for hot water is a good installation scheme. 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 the tank). On the other hand, hot water for consummators is charged from the top of the accumulator, where the highest water temperature is kept. This delivers useful energy on demand.

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. Most of the 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 the same place.

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 of 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 installation with special monitoring and controlling system is built in South-West University "N. Rilski" (SWU) – Blagoevgrad. The scheme and description of installation is presented in [6]. The main target of monitoring and controlling system is to ensure possibility to: work in direct and indirect regime with different heat exchange area and location of serpentine unit in the tank; change angle of collectors toward by horizon and azimuth; regulate some operating parameters (fluid flow rate); measure all important parameters, influenced the system performance.

The test tank is a vertical cylindrical tank made of stainless steal material. In the tank are built three copper serpentines along 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.

Monitoring system includes 12 thermo sensors assembled in accumulation vessel, 6 thermo sensors in collector circle, one thermo sensor for 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 heatmeter. 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.

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. Hence, one-dimensional modeling is a possible alternative, because of its simplicity and sufficient accuracy of computational procedures.

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

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.1,. The sectors are numbered from the bottom to the top of tank. Different sectors contain different parts of heater area (serpentine). This means that in sectors work different heat sources (heat exchange area).

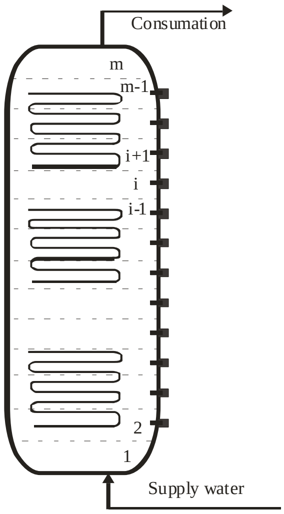

Fig.1. Schematic diagram of the tank

Hot water is consumed from the upper sector of the tank. Consumed water quantity is compensated 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 the water in the sector. This process occurs in all next sectors of the tank. The temperature change in sectors by discharging process (water consumption) can be written by:

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

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

In the same time, another process is taking place - the thermal charging process (hot water accumulation). The heat from solar collectors is transferred to the water in the tank by serpentine elements. This causes temperature rise in tank. Temperature rise depends on 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:

$$T_{i,ac} = T_{i,ac}{}' + \frac{K_{i,ser} F_{i,ser}}{\rho V_i c_p} (T_{i,av} - T_{i,ac}{}') \nabla \tau \,, \qquad (2)$$

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

Overall heat transfer coefficient $\boldsymbol{K_{iser}}$ for serpentine element includes convective coefficients $\boldsymbol{h_f}$ and $\boldsymbol{h_{free}}$, corresponding to the forced circulation in serpentine pipe and free convection from external surface and conductive transfer parameters for serpentine wall:

$$K_{i,serp} = \frac{1}{\dfrac{1}{h_f} + \dfrac{\delta_s}{\lambda_s} + \dfrac{1}{h_{free}}} \,, \ [\mathrm{W/m^2\,K}] \qquad (6)$$

where $\boldsymbol{\delta_s}$ and $\boldsymbol{\lambda_s}$ are serpentine wall thickness and conductivity coefficient of the serpentine material.

Convective coefficients $\boldsymbol{h_f}$ and $\boldsymbol{h_{free}}$ depend on fluid temperatures, which are unknown values in the beginning of the calculations. Known parameters for calculation start are the inlet fluid temperature for serpentine (outlet collector temperature) and water temperature in accumulator (temperature distribution in accumulator). Initial temperature distribution in accumulator must be adopted in the beginning of the calculations (initial conditions). This predestines the calculation consequence - from the top to the bottom of accumulator because the inlet of serpentine is in top region of accumulator. Calculation begins for the top accumulator sector with the known fluid temperature in entrance of serpentine element. Iteration procedure for transfer coefficient $K_{i,serp}$ is adopted.

Inlet fluid temperature $T_{i,in}$ in i-sector is known - the outlet temperature from the previous (upper) serpentine element (sector $i+1$). It stays constant in iteration process. For the top sector inlet fluid temperature in serpentine element is determined by solar collector's performance. The outlet temperature $T_{i,out}$ depends on transferred heat energy in sector and is determined by equation (13) in last iteration step.

Mathematical model for solar collectors is well-established matter and detailed information can be fond in solar energy publications. Outlet temperature of working fluid for solar collectors is defined by next equaton [1]:

$$T_{sol,out} = \frac{F_R}{m \cdot c_p}[q_s(\tau \cdot \alpha)_e - U_L(T_{sol,in} - T_a) \qquad (14)$$

where F_R is heat removal factor, m – mass flow of working fluid, $(\tau\alpha)_e$ – effective transmittance absorbing coefficient for optical part of solar collectors, q_s – solar radiation flux for tilted surface [W/m^2], U_L – overall collector heat loss coefficient [W/m^2 K], T_a – ambient temperature. Inlet temperature for solar collectors $T_{col,in}$ is the outlet temperature from the bottom serpentine element. Because of dependence between inlet temperature of working fluid for serpentine and inlet temperature for solar collectors (outlet temperature for serpentine), new iteration calculations are needed.

Special simulation algorithm binds the collector and accumulator models in a working unit. It takes into account the heat losses in pipes and accumulator. Computer program is created to manage the theoretical calculations.

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.

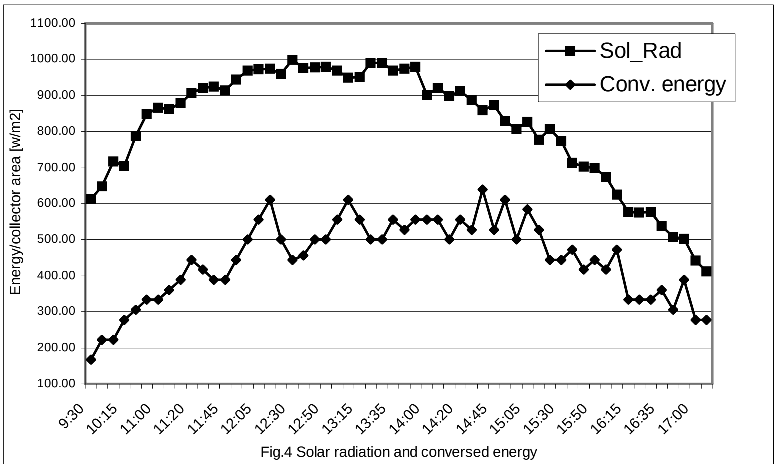

Fig.4 Solar radiation and conversed energy

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

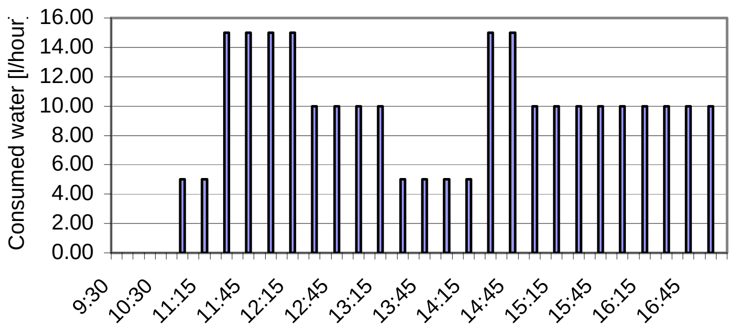

Fig.3. Distribution of consumed water

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.

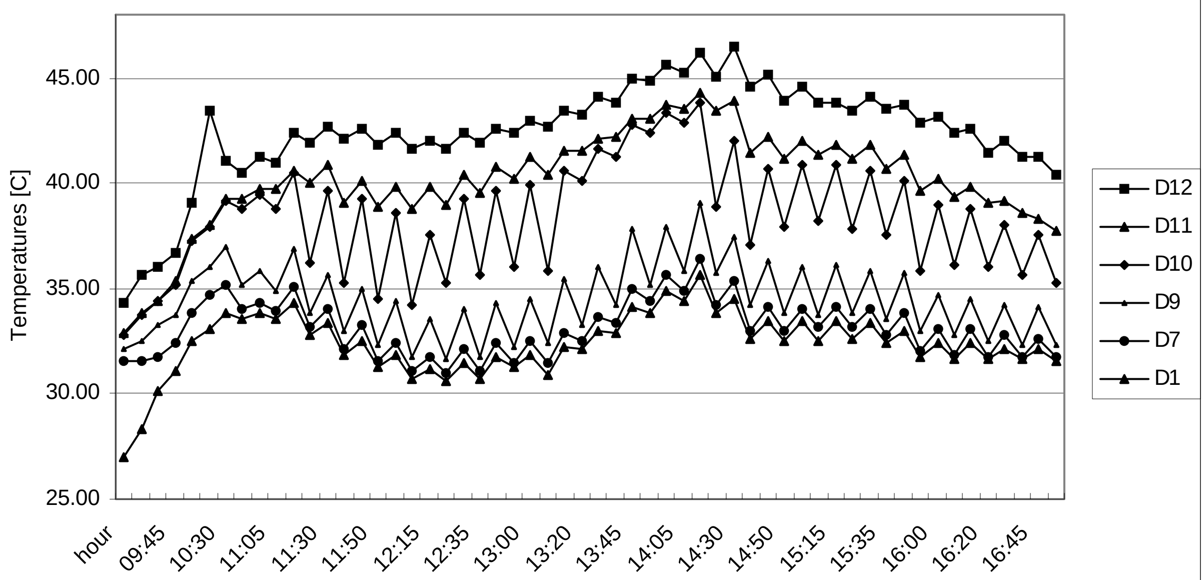

Fig.5 Temperatures in tank - tw o serpentines

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.

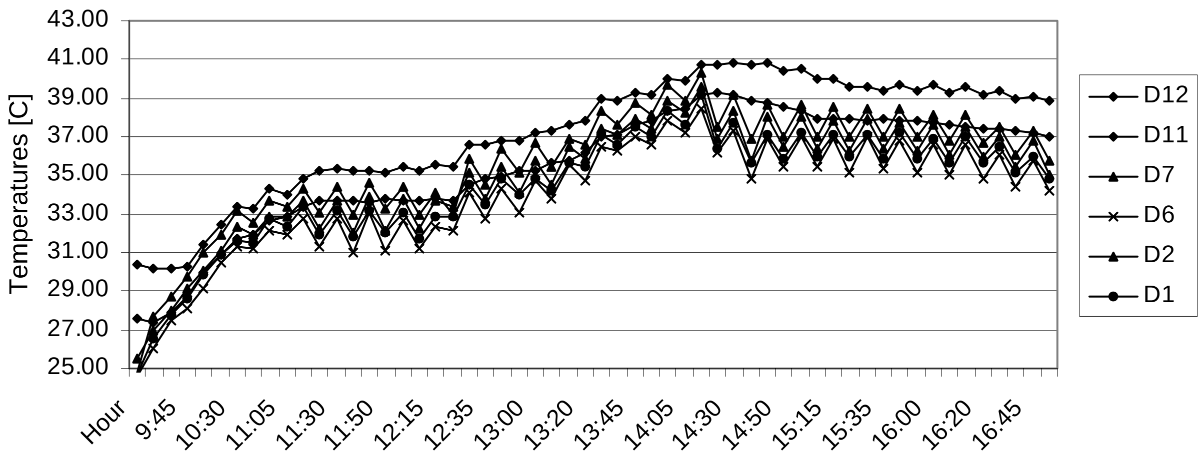

Fig.6. Temperatures in tank - serpentine in bottom

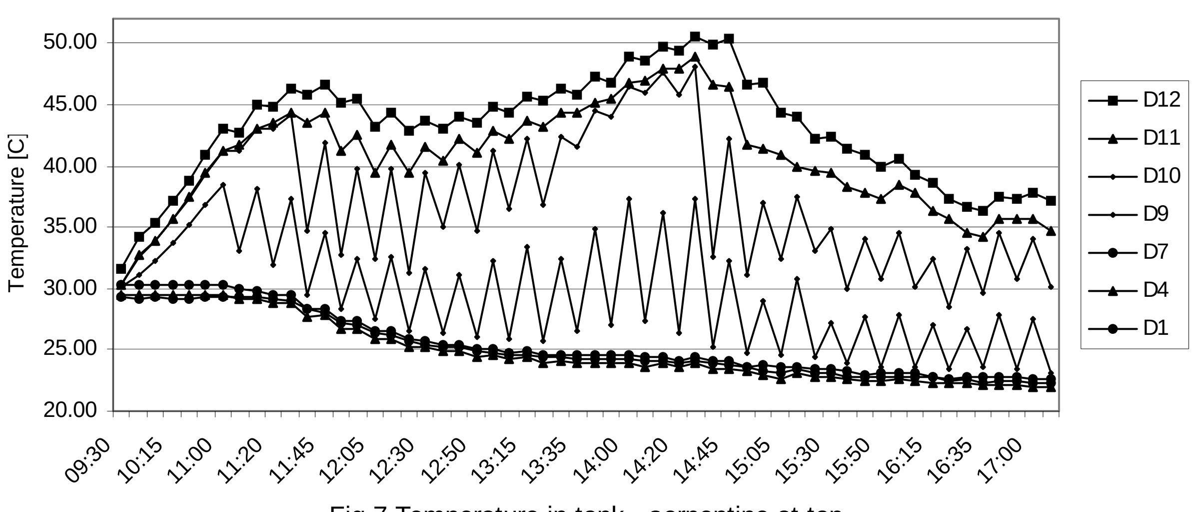

Fig.7 Temperature in tank - serpentine at top

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. Economical calculations

The aim of investigations carried out in this work is to optimize the use of small solar heating systems for domestic sector. Demonstration project has been realized to determine the investment cost and expenditure for construction and mounting. In a dialogue with Bulgarian solar collector manufacturers and importers, a price relation for small solar heating systems was found:

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)
6. Shtrakov St.,A. Stoilov, Solar hot water installation with stratified accumulation,