Experimental and theoretical study of solar accumulator with heat exchange serpentine

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Abstract – Experimental and theoretical study of solar accumulator with heat exchange serpentine is performed and useful information for thermal processes is received. Practical recommendations for construction and regimes of exploitation for hot water solar installation with thermal stratification are formulated in this work. The main concept of investigation is to optimize the stratified regime of thermal accumulation and constructive parameters of heat exchange equipment (heat serpentine in a tank). Accumulation and heat exchange processes were investigated by theoretical and experimental means. An experimental solar module for hot water was built and equipped with sufficient measure apparatus. Special mathematical model was composed to simulate the energy transfer in a stratified tank. Extensive numerical and experimental tests were carried out. A good correspondence between theoretical and experimental data arrived.

Keywords: Stratified accumulation, solar hot water installation.

1. Introduction

Solar hot water installations have become popular solar applications in Bulgaria for the last years. There are good climatic conditions in Bulgaria for all seasons' application of solar energy in domestic and public sector. For small scale solar installations, preliminary used in the domestic sector, thermally stratified storage tanks for hot water are a good installation scheme. Stratified storage tanks are more thermally and economically effective.

For all seasons' applications it is necessary to use an indirect solar scheme for heat accumulation, because a special unfreezing work fluid must be used. In small solar installations this can be realized by serpentine heat exchanger mounted in volume of water accumulator. Free convection heat exchange process is in main importance for solar energy conversion in such solar installations. Accumulator volume and shape is also of great importance for water temperature stratification along the accumulator height. Accumulator must be vertically situated and the height is the main constructive parameter assuring good and sustainable temperature stratification.

Solar installations with stratified tanks and heat exchange by included serpentine have advantages, because the stratification's degradation, caused by fluid mixing in charge phase is practically eliminated. Moreover, the place of heat exchange process in the tank can be regulated with a serpentine location. The serpentine can be situated in upper, middle or bottom part of the tank.

When the serpentine is mounted in the bottom part of the tank, high energy efficiency of solar collectors can be realized. It is because the relatively low temperature in the bottom layers in the accumulator extracts maximal heat from working fluid, circulating through the collectors. Thereby the inlet temperature for solar collectors is relatively low and energy efficiency will be high. In this case however, considerable thermal stratification can't be reached, because the natural convection transfers the heat upwards in all the volume of the accumulator.

In contrary, if the serpentine is located at the top part of the accumulator, the maximal thermal stratification can be realized. It is because the heat is accumulating in upper water layers and hot water with lower density is not transferring down to lower water layers. However, this also is not a good strategy for accumulation scheme in the solar installation, because the bottom part of the accumulator is not efficiently used (it does not really take part in solar accumulation). The inlet temperature for solar collectors will be higher and energy efficiency will be low.

Such a situation is in fact also, when the serpentine is mounted in the middle part of the accumulator, because the volume under serpentine is thermally separated from heat accumulation process.

All that indicates that the efficient way for solar accumulation with thermal stratification needs the serpentine to be divided in two or three parts. These must be located in different regions along the height of the tank – in the top of accumulator for ensuring quick temperature rising by heat exchange with outgoing working fluid from solar collectors and in the bottom part for fully extracting the heat from working fluid.

Energy efficiency of thermally stratified accumulator depends more sensitively on the consumption regime of hot water in solar installation. It is important whether the hot water consumption is performing in short time (restaurant, school regime) or it is prolonging the long period of the day and night (home or hotel regime).

Investigation of commented characteristics and parameters for solar installation is very difficult, because the experiments need a long time and numerous variants of constructive and regime parameters' combinations. One useful solution for this problem would be developing a mathematical model, which has to be verified by many experiments in a wide range of variation of parameters.

A variety of models and experiments to assess the efficiency of stratified tanks has been produced in many laboratories and functioning solar installations [1,2]. 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. Solar installations with serpentine exchanger, located in water accumulator, are investigated rarely, especially with assessing temperature stratification. In such solar installations the thermal exchange process and heat accumulation perform simultaneously at the same place. This leads to the appearance of some special physical effects, which define different energy efficiency in the exploitation period. Experimental and theoretical investigations, made in this work are intended to widen the knowledge about commented above problems.

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

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. The tank and connection pipes are well insulated.

In the tank are built 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.

Monitoring system includes 12 thermo sensors assembled in accumulation vessel, 6 thermo sensors in collector circle and one thermo sensor for measuring the ambient air temperature. Solar meter 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 the 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.

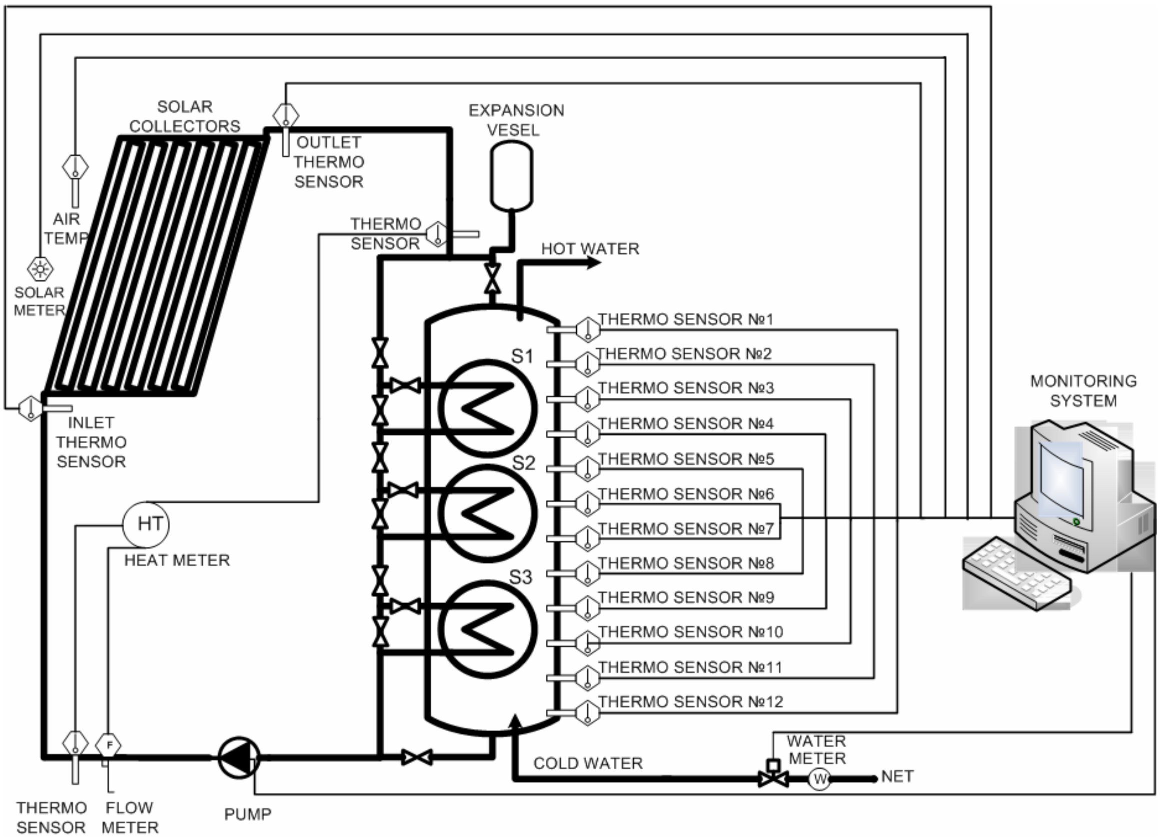


Fig.1. Schematic diagram of the test apparatus.

3. Theoretical modeling

Theoretical model for heat accumulation in solar thanks with serpentine is based on natural convection of an incompressible Newtonian fluid enclosed in cylindrical vessel. Natural convection is caused by transferring a heat from serpentine to the water in tank. This process is influenced by the water circulation in time of hot water consumption, heat conductivity in water and heat losses to the ambient.

Heat and mass transfer processes in water accumulators for hot water solar installations are very complicated, because of mixing different mechanisms of heat and mass exchange in volume – water consumption, natural convection locally round the serpentine and globally in all the volume, heat conductivity in water, forced convection in serpentine and heat losses to the ambient. It is impossible, all this processes, to be described in one mathematical system. In such complicated physical systems special Operator Splitting Method and splitting schemes have to be applied to split the general model into separated sub-problems. The splitting scheme is based on the well-known in physics superposition mechanism, which decouples heat and mass transfer phenomena and difficulties associated with non-linearity in most of the used equations. It means that different heat and mass transfer mechanisms are modeled separately and act consequently in given time period.

A 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. Detailed information of the mathematical model and computer program is presented in [3,4] .

Special simulation algorithm has been developed to bind the collector and accumulator models in a working unit. It takes into account the heat losses in installation's pipes and elements. A computer program is created to manage the theoretical calculations.

To verify the applicability of the above proposed technique, a large number of numerical examples have been carried out. The splitting scheme of mathematical model allows making verification of different physical processes of thermal accumulation. For example, if the serpentine is located in the bottom part of the vessel and there is not hot water consumption the natural convection in accumulator can be investigated separately from the other processes. It is the main process, which transfers heat from down layers upward and determines temperature distribution in accumulator in this case. Other processes play secondary role in integral performance of solar installation. In [3] are shown results for good correspondence between theoretical and experimental result which has been achieved.

4. Thermal analyses of constructive parameters of heat accumulator.

The first kind of thermal analysis carried out with experimental and theoretical instruments was to study the influence of serpentine location in accumulator on the installation performance. Experimental module allowed performing different combination of serpentine location (three parts of serpentine can be included or separated from installation scheme).

Preliminary analyses for constructive parameters of heat exchange serpentine sifted two variants of practical importance for serpentine location in accumulator volume. The first variant is to locate the serpentine in bottom part of accumulator – 'economical' variant (fig. 2a). The second one is the 'effective' variant – disposition the serpentine in two parts – in bottom and top region of the accumulator (fig. 2b). In the first case there is only a partial stratification formed only by lifting the hot water to the top of the tank in the consumption phase (lifting hot water from bottom part by consumption from upper region of accumulator). In the second case the upper part of serpentine acts as a quick heater and determines effective temperature stratification.

Experiments and theoretical investigations show that the stratified temperature distribution in thermal accumulator for solar hot water installations influence on the thermal processes more strongly in case of exploitation in non regular condition. That is when the climatic parameters vary from day to day or when hot water consummation is variable. In case of regular exploitation (the climatic conditions are the same for succession of days and hot water consumption is regular) the process can be named 'quasistationar' and temperature stratification is not so important. In the next analysis results are shown for irregular and 'quasistationar' conditions.

In fig. 3 it is shown variation of the utilized solar energy for four days period with regular conditions, starting from initial uncharged state (temperature in accumulator is equal to the temperature of water supply net). Utilized energy is registered as consumed energy (down curves) and as solar collectors production (upper curves). Difference in energy values in the beginning of process is determined by the thermal accumulation and heat losses in the beginning of charge process. Data is registered for summer period (August) and daily hot water consumption of 150 l/day.

It is shown that in the beginning (first day of the period) the difference between utilized from solar collectors energy and consumed energy is significant. When in accumulator are mounted two serpentines there is a good energy distribution in the volume of accumulator of the utilized from solar collectors energy and consumed energy is bigger. It is shown also in the curve of solar fraction (part of energy delivered by solar collectors) from the consumed energy (fig. 4). In the first day this portion is small. This is a typical work of installation in irregular regime. When two serpentines are mounted in the heat accumulator it is received a better correspondence between consumed energy (hot water) and solar energy gain in irregular conditions.

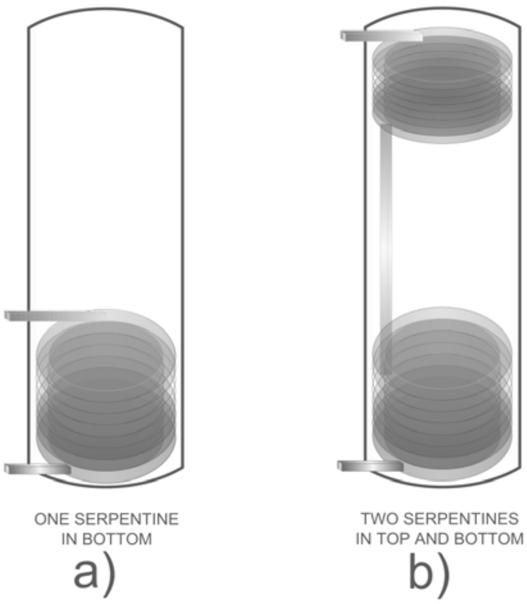


Fig.2. Different schemes for serpentine location in storage tank, study in this paper.

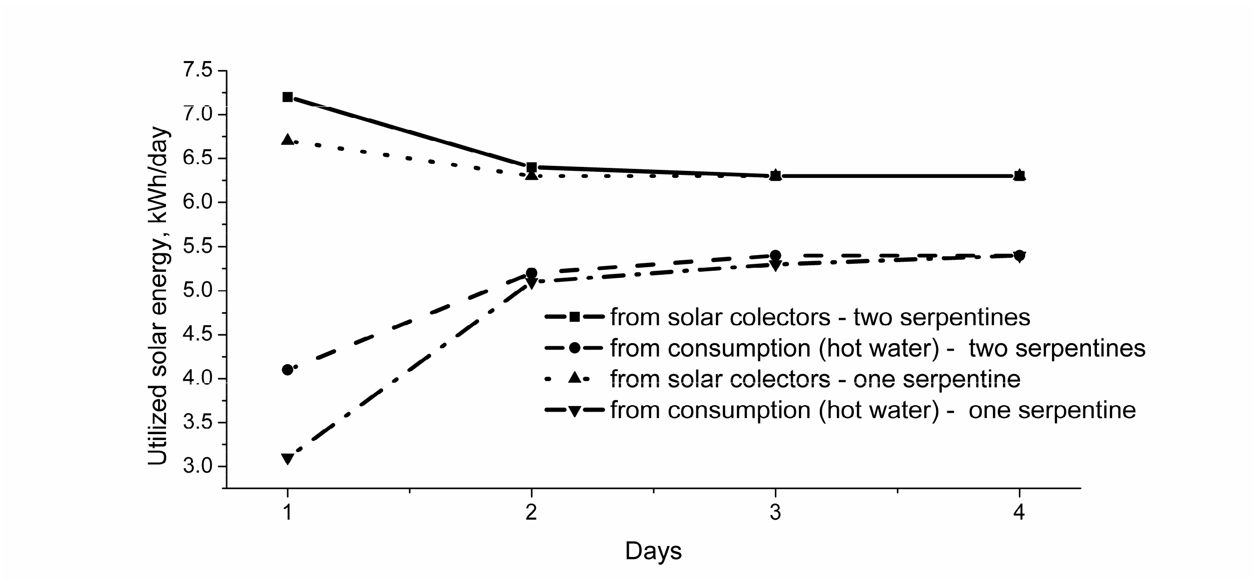
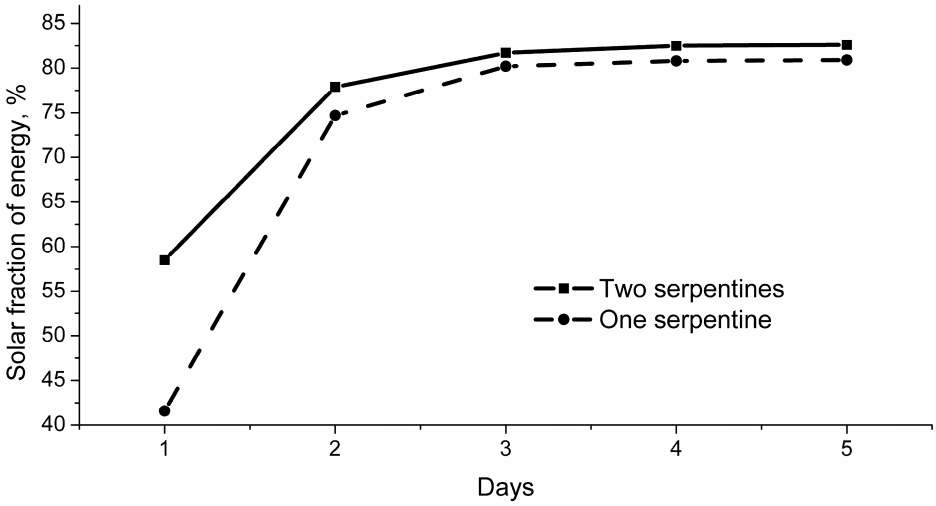
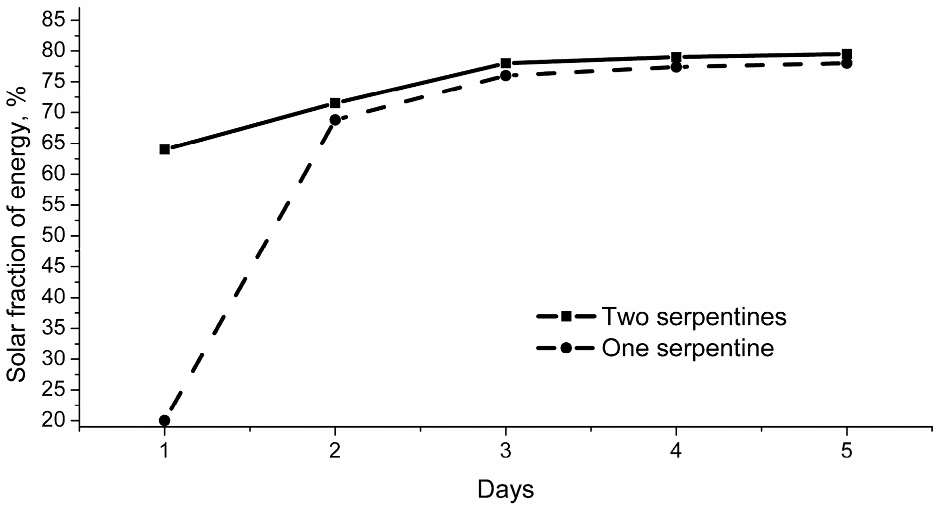


Fig. 3. Utilized solar energy from solar collectors and consumption of hot water (home graph) in different schemes for serpentine location: one serpentine in bottom and two serpentines in top and bottom (fig.2).

The physical phenomena in this case can be described by thermal accumulation. In the first day of installation work (after full discharge), the solar collectors produce more energy, but part of this energy is accumulated in heat storage. Accumulated energy is ready for consumption in the next days. In the same time there is a shortage of energy for consuming water because of the lack of coincidence between time of solar shining and hot water consumption.



a)



b)

Fig.4. Solar fraction of energy (%) of consumption of hot water home graph - (a) and restaurant graph - (b) in different schemes for serpentine location: one serpentine in bottom and two serpentines in top and bottom (fig.2).

Energy shortage is bigger in case of serpentine disposition in bottom region of accumulator. In the morning there is not accumulated enough energy in the upper part of accumulator and consumption is accompanied by using auxiliary energy. In case of serpentine disposition in upper and bottom region there is heat transfer in upper part of accumulator in morning hours and energy accordance between solar gains and consumption is better. The upper part of serpentine is used as a quick heater.

Influence of the consumption regime (consumption graph) on the unsteady process of solar energy utilization in stratified accumulators is shown in the next figures. On figure 4a is shown variation of solar fraction for typical hot water consumption in a family house. Here differences between construction with one and two serpentines is significant and the time for temperature stabilization is bigger.

On the next figure (fig. 4b) it is shown analogous results for solar installation, working with consumption graph for typical restaurant (with short and sharp consumption).

Because of specific hot water consumption distribution influence of serpentine disposition is stronger. During the first day there is basically accumulator charging in the case of disposition of serpentine in the bottom part of storage. The solar part of consumption energy is only 20%. When the serpentine is located in two regions of accumulator there is a good energy distribution in time and the solar part of consumption energy achieves up to 60% in the first day of process.

These results are confirmed by the daily temperature distribution in accumulator volume.

In the next figures (fig.5 and 6) it is presented twenty-four hours distribution of water temperature for specific layers on the height in accumulator. These data are referred to the first night and day of the analyzed period (beginning of loading the accumulator - fig. 5) and for a 'quasistationar' regime (the fourth twenty-four hours - fig.6).

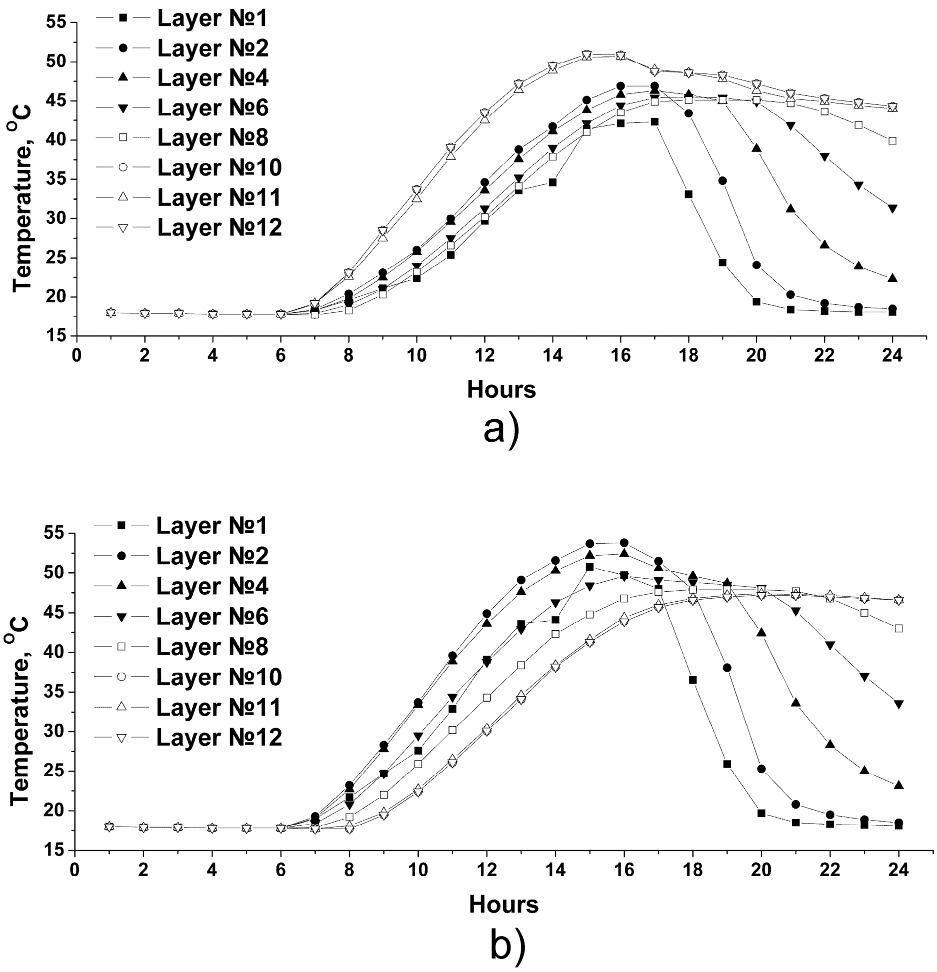


Fig.5. Temperature distribution with two serpentines - (a) and one serpentine - (b) (first 24 hours).

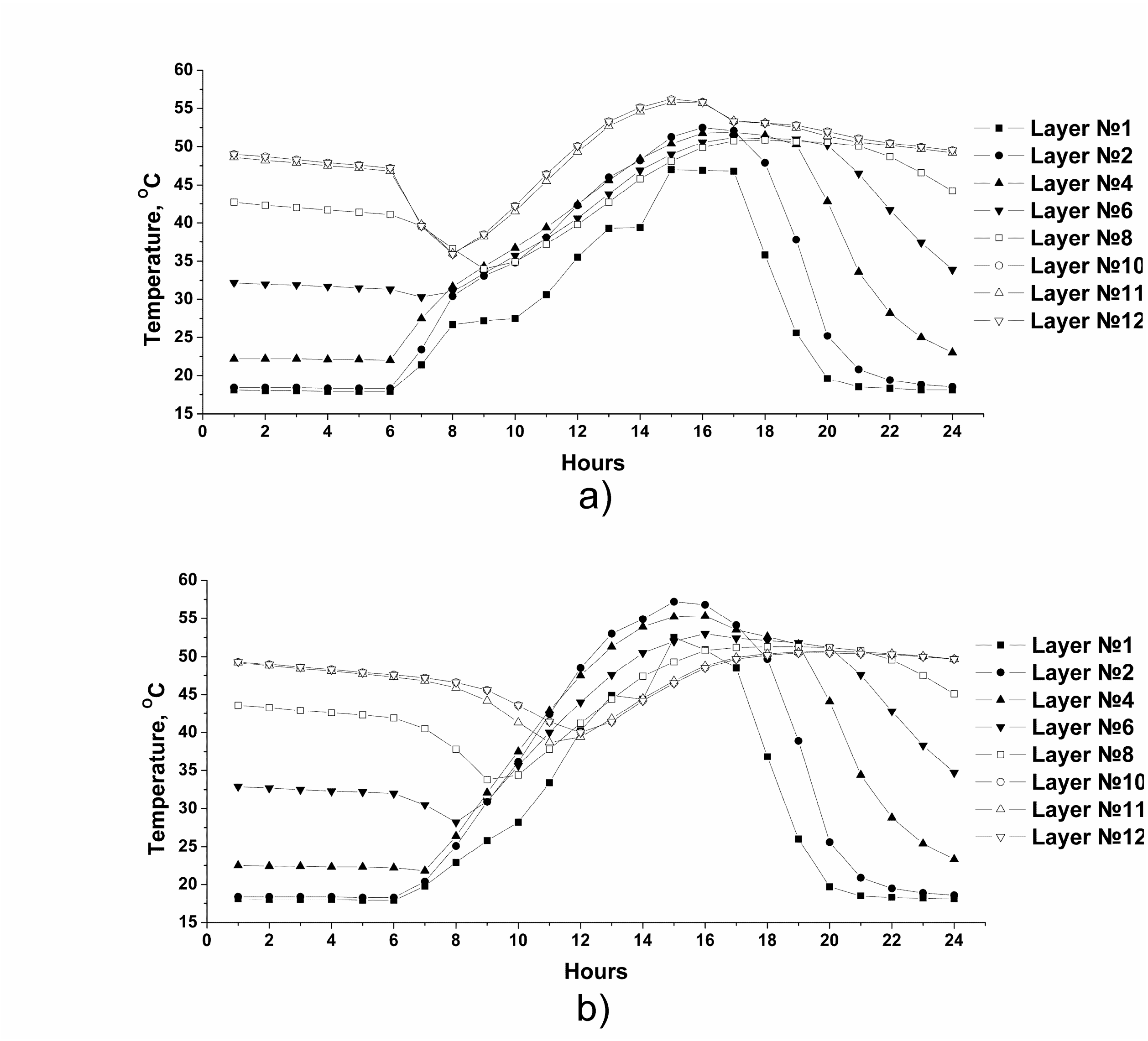


Fig. 6. Temperature distribution in different layers of the storage tank in cases of two serpentines - (a) and one serpentine - (b) (last 24 hours).

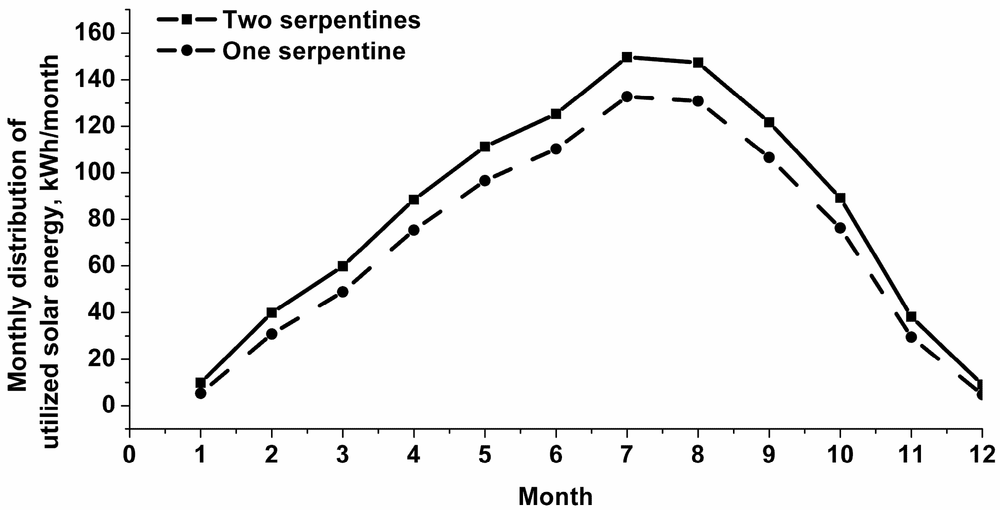
What can be seen from the graphics performed is that in an accumulator with two serpentines the highest water temperature is sustained in the highest horizontal layers (layers N11 and N12) during the whole period of loading the accumulator. In an accumulator with a serpentine location in the bottom layers (N1 – N4) almost at the end of the twenty-four hours, after the consuming of the bigger part of daily rate, hot water from the bottom part of accumulator moves upwards and receives natural temperature layering of water (after 20 hours). This reflects on the energy efficiency of the solar installation, as it can be seen from long-term analysis and next figures.

5. Long-term assessments of energy efficiency

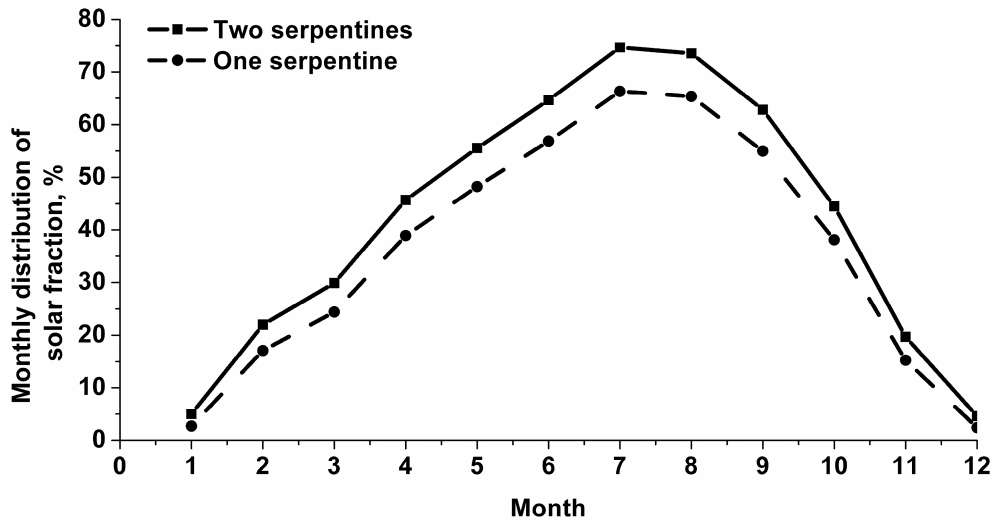
Apart from short-term characteristics of solar installations disposition of heat exchanging serpentine, it influences on long-term characteristics of systems. Long-term characteristics can be assessed depending on the exploitation regime of solar installations. If the solar system is used the whole year, the assessment should be performed for a whole-year-regime of exploitation. In some cases solar installations are used only during the summer and it is performed a seasonal assessment for the installation exploitation.

Assessment for energy efficiency in solar systems is performed about the value of the energy used by solar installations (W_{year}, W_{season}) and about the part of the energy necessary for water heating, which is provided by the sun (a percent of solar fraction – parameter f). As the period of experimental researches is not sufficient (about 2.5 years) and climatic characteristics for this period are not representative, assessments for energy efficiency are performed with the help of simulation calculations with the developed program for solar simulations, described above. There is used data about the sunshine duration for the area of town of Blagoevgrad, which are representative.

Climatic data represent statistic average data about the twenty-four-hour course of changing solar radiation and environment temperature. That is the reason why simulation calculations are performed for all the months the installation is exploited and energy indicators are processed during the period utilized (a year or a season).



a)



b)

Fig.7. Monthly distribution of utilized solar energy – (a) and solar fraction – (b)

In Fig. 7a it is shown a graph of the change in monthly amount utilized from the solar system energy for both variants available to the heat exchanging serpentine – at the bottom and the upper part and only at the bottom part of accumulator. Both variants are with identical heat exchanging surface of the inserted serpentine. In this way it is accounted only the influence of the serpentine position. Results are referred to the graph of consuming type "family house".

In Fig. 7b it is shown the change of monthly percent of solar fraction for both variants.

From the graphs performed it is seen that when the serpentine is divided in two parts set in the bottom and the upper part of accumulator, summary efficiency of the exploitation of installation is better during the whole exploitation period of the system. It is due to provided better temperature stratification in the heat accumulator, especially in instationary performance of the system. In this way better exploitation characteristics of the solar system are provided. In annual aspect data about energy efficiency with both variants are given in table 1.

Data about influence of the serpentine position in other work conditions of the system (graphs of consuming, angle of inclination of solar collectors, daily rate for consuming hot water, etc.) are performed in the following analyzes and researches. The main conclusion which can be made from these studies is that in appropriate position of the heat exchanging serpentine it is possible to improve significantly the temperature stratification and thermal efficiency of hot water solar installations.

Table 1. Average year characteristics of installlation

Installation type	Year utilized energy *kWh/year*	Average solar fraction [%]	Average energy efficiency of installation, %
2 serpentines	990	42	45.6
1 serpentine	848	36	39.1

6. Influence of accumulator volume on the thermal efficiency in solar installations

Another important parameter influencing the energy efficiency of solar installations with stratified accumulators and serpentine heat exchanger is accumulator volume. Temperature distribution of consumed water is realized in accumulator volume (on the height of tank) and it is recommendable to investigate influence of this parameter.

In the beginning, it can be marked for the influence of accumulator volume on the thermal efficiency of solar installations, that the volume of thank would not exceed daily norm of hot water consumption. If the volume of thermal accumulator is bigger than the daily consumption of the hot water there will be an unused volume ('parasitic volume'), which doesn't take part in daily consumption and only will generate heat losses.

Secondly it must be noted that influence of accumulator volume on the thermal efficiency in solar installations is stronger for the stratified accumulators in comparison with ordinary heat accumulators. That is because in the stratified accumulators heat energy is volume distributed. When the heat exchanger is serpentine, mounted in accumulator volume, there is not water flowing in charge process. This guarantee thermal stratification stability and there is not need for water quantity exceeds the daily consumption norm.

By means of experimental and theoretical investigations it was studied the influence of accumulator volume with constant daily water consumption. In the next figures there is shown data, which indicates the influence of accumulator volume on the solar installation efficiency.

In Fig. 8 it is shown change in the percent of the solar fraction for standard hot water installation with a daily rate of consuming – 150 l/day. What can be seen is, that maximum exploitation efficiency the installation has in volume of heat accumulator 100 l.

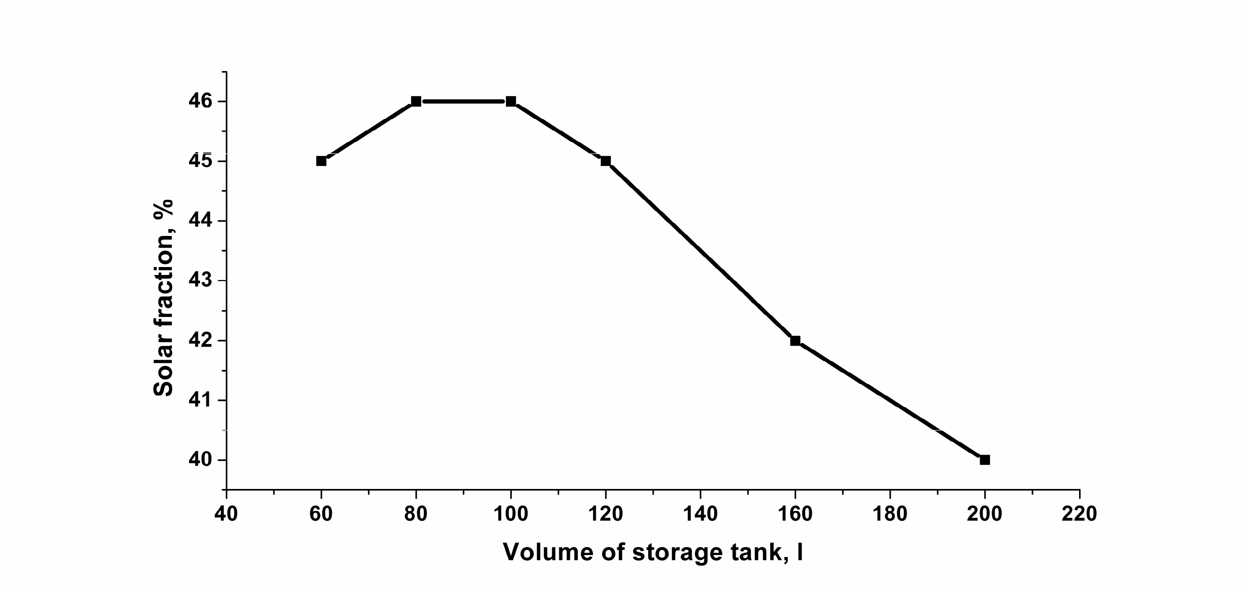


Fig.8. Influence of the accumulator volume (hot water consumption 150 l/day)

The change of exploitation efficiency of installation in this case is due to different temperature regime set in the stratified accumulator. In less accumulating volumes the system reacts faster to the change both in hot water consuming and availability of solar radiation. In Fig. 9a and Fig. 9b it is shown twenty-four-hour change in the temperature in two layers of the accumulating volume – the upper layer (layer N12 – Fig.9a) and middle layer (layer N8 – Fig.9b) in different accumulating volumes. Researches are about a certain exploitation regime of the system after 5 consequent days with almost permanent parameters of the climate and hot water consuming. It is seen that in a very small volume (60 l) twenty-four-hour temperature change is the biggest. In this case there is practically no heat accumulated for night period. In bigger volumes (as much as daily rate for hot water and bigger) there appears a temperature equality which eliminates the advantages of stratified accumulator.

Experimental and numerical researches which have been carried out show that the optimal value of the volume of heat accumulator is a function of daily amount consumed hot water. Other factors influence as well, but they only replace the curve of utilized energy or a percent sun fraction in positive or negative direction. The character of dependence is kept and the recommended value of the volume of heat accumulator can be set in those limits:

$$V_{ac} = (0.55 \div 0.65) V_{cons} ,$$

where $\mathbf{V}_{ac}$ is a volume of a heat accumulator (m^3) and V_{cons} is a daily consuming of hot water (m^3/day).

7. 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 configurations 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 the tank improves thermal efficiency up to 15-20%. This can result in using smaller collector area to prepare hot water.

Thermal efficiency in solar installations is the 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.

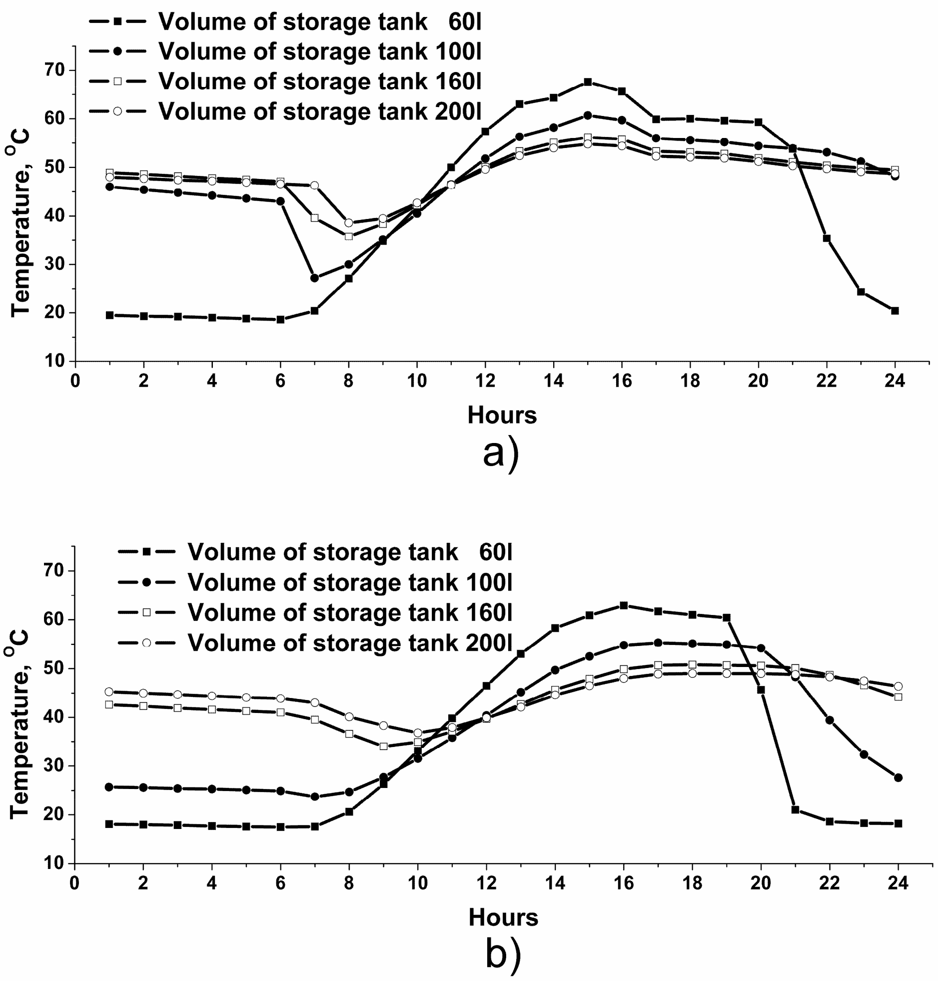


Fig. 9. Temperature distribution in high layer (№12) – (a) and middle layer (№8) – (b)

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