Experimental and Numerical Research of Thermal Processes in the TST Tanks with Thermal Oil and a Phase Change Medium

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Abstract: This paper surveys a part of the activities (performed during the realization of the third year of project III 42011 financed by the Ministry of education and science of the Republic of Serbia) on the development of TST whose storage medium melts at the atmospheric pressure, enabling on that way the use of the energy of phase change for energy storage. The original experimental setup adapted for use of paraffin as a phase change media (volume 77 dm^3, heating power 2.4 kW) was modified by inserting four vertically positioned tubes (inner diameter 120 mm) filled by paraffin into the tank. The rest of the tank was filled with thermal oil. Storage media was cooled by the air which circulates around the tank. The research was realized in two phases: a) with thermal oil as the only storage media; b) with the combination of paraffin and thermal oil. Inside the main body of the tank the temperature measurements were performed by 12 thermocouples, 4 along the tanks height and 3 along the tank radius, and inside the cylinder filled with paraffin with 4 vertically positioned thermocouples. For the development of the numerical model of heat transfer and fluid flow processes in TST a commercial numerical package Fluent 12.1 was used, since it possesses its own routine for computation a temperature and flow fields in TST with the change of phases, but also it allows to user to implement the package with its own model by using the user define functions. Measurements and the numerical computation were performed for non-stationary as well as for stationary working regimes. A good agreement between the numerical and experimental results was achieved.

Keywords: TES, Measurements, Numerical model, Phase change, Thermal oil, Paraffin

1. Introduction

Thermal storage tank (TST) represents an essential part in the optimization of many facilities that uses one of the renewable energy resources, like biomass, solar energy, etc. As a rule any of them have at least one, and very often even more TST. This is due to the fact that energy production and energy consumption varies enormously during the day. For example, a greenhouse heating system is characterized by very rapid changes in environmental conditions such as the changes in air temperature, intensity of solar irradiation, wind speed, changes caused by a diurnal cycle etc. TST enables accumulation of the surplus heat generated during the periods of reduced heat demand, acting as additional heat source in critical periods of low ambient temperatures. Important part of the optimization of the whole facility represents the proper dimensioning of TST, choice of the working media and means of the heat storage, since the costs associated with the installation of TST in the facility represents 25-30% of the overall system investments. In thermal energy storage, produced energy is transformed into the internal energy of the storage media, in the form of the sensible heat, latent heat, or both [1]. The most common type of TST uses water as working media, since it has a huge heat capacity. Still, the stored energy in it is only of the sensible type, with relatively low temperature of the heated water (up to 100 °C). It requires large volume for storage also, especially in cases when allowable temperature difference in heating is small. The solution of this problem is to use either latent heat storage or to use some liquid with relatively high heat capacity and much higher boiling temperature.

Latent heat storage is in some respects more attractive than sensible heat storage, due to its high storage density with small temperature swing and possibility to supply energy source on high temperatures (300 °C and even more), where it is necessary. The comparison between latent and sensible heat storage shows that using latent heat storage, storage density typically 5 to 10 times higher can be reached. Phase change materials (PCM) storage volume is two times smaller than that of water. Its disadvantages are lower thermal conductivity of PCM-s compared to water, variation of the in thermo-physical properties under many repeated cycles of heating and cooling, volume change, high cost of the storage media etc. Comparative study of both types of heat storage was given in [2]. Generally, speaking about the desirable thermo-physical, kinetics and chemical properties which PCM-s should accomplish are [3]:

Thermo-physical Properties

a) Melting temperature in the desired operating temperature range.
b) High latent heat of fusion per unit volume so that the required volume of the container to store a given amount of energy is less.
c) High specific heat to provide for additional significant sensible heat storage.
d) High thermal conductivity of both solid and liquid phases to assist the charging and discharging of energy of the storage systems.
e) Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problem.
f) Congruent melting of the PCM for a constant storage capacity of the material with each freezing/melting cycle.

Kinetic Properties

a) High nucleation rate to avoid super cooling of the liquid phase.
b) High rate of crystal growth, so that the system can meet demands of heat recovery from the storage system.

Chemical Properties

a) Chemical stability.
b) Complete reversible freeze / melt cycle.
c) No degradation after a large number of freeze / melt cycles.
d) Non-corrosiveness to the construction materials.
e) Non-toxic, non-flammable, and non-explosive materials for safety.

Moreover, low cost and large-scale availability of the PCMs is also very important. Although in principle all types of phase changes are possible, of practical interest are only solid-liquid and solid-solid (change in the structure of crystalline grid). Solid-liquid transformation has smaller latent heat than liquid-gas transformation, but the volume change is less than 10%, and praxis showed that it is economically attractive for heat storage. The present work restrained on research of this type of latent heat TST only. In it, a detailed study of temperature profile in TST, characteristics and mechanisms of heat transfer properties as well as thermal properties of the working media needs to be performed. Such study has to be carried out in various operating regimes, i.e. in cases when heat is being transferred to the TST, when it is being transferred from it, and finally when both processes happen simultaneously. It consists of both experimental numerical CFD study, [4]. The results of the study represent basis for the choice or development of the computer tool for the proper TST dimensioning.

This paper surveys a part of the activities performed during the realization of the third year of project III 42011 financed by the Ministry of education and science of the Republic of Serbia. These activities represent natural continuation of those performed in the second year of project realization, where TST prototype with phase change media was developed. A cylindrically shaped TST was filled with heat storage media (paraffin), heated in direct contact with coaxially positioned cylinder, with the electrical heater positioned inside it. Although paraffin as working media (its physical properties were given in Table 1) proved to be very suitable up to temperatures of 200 °C, its direct contact with the heating cylinder (whose temperature was kept between 350 and 450 °C, depending on heating power) caused local evaporation of paraffin, close to the heater. In order to avoid this problem, authors of the work decided to put paraffin in closed cylinders vertically positioned in TST prototype. The rest volume of the prototype was filled with thermal oil, which in this case served as interface between the heater and paraffin, as well as heat storage media.

Table 1. Physical properties of paraffin

T_{melt}	ρ_s at 15℃	ρ_l at 100℃	r_l	c_p	k
°C	kg/m^3	kg/m^3	kJ/kg	kJ/kgK	W/mK
55	900	760	179	2.9	0.24-0.27

Thermal oil is very often used as an alternative to water as sensible heat storage media, due to its higher boiling temperature (about 160 °C), which can double or even triple the temperature difference between hot and cool media. There are also facilities where the temperature of the working media is higher than 100 °C, and consequently it is impossible to use water in tanks on atmospheric pressure. Thermal oil properties as functions of temperature are given in Table 2.

Table 2. Physical properties of thermal oil

T	ρ	c_p	ν	k	a	Pr	β
°C	kg/m^3	kJ/kgK	m^2/s	W/mK	m^2/s	-	K^{-1}
0	899.12	1.796	0.00428	0.147	0.911 x 10^{-7}	47100	0.70 x 10-3
20	888.23	1.88	0.0009	0.145	0.872 x 10^{-7}	10400	
40	876.05	1.964	0.00024	0.144	0.834 x 10^{-7}	2870	
60	864.04	2.047	0.839 x 10^{-4}	0.14	0.800 x 10^{-7}	1050	
80	852.02	2.131	0.375	0.138	0.769 x 10^{-7}	490	
100	840.01	2.219	0.203	0.137	0.738 x 10^{-7}	276	
120	828.96	2.307	0.124	0.135	0.710 x 10^{-7}	175	
140	816.94	2.395	0.08	0.133	0.686 x 10^{-7}	116	
160	805.89	2.483	0.056	0.132	0.663 x 10^{-7}	84	

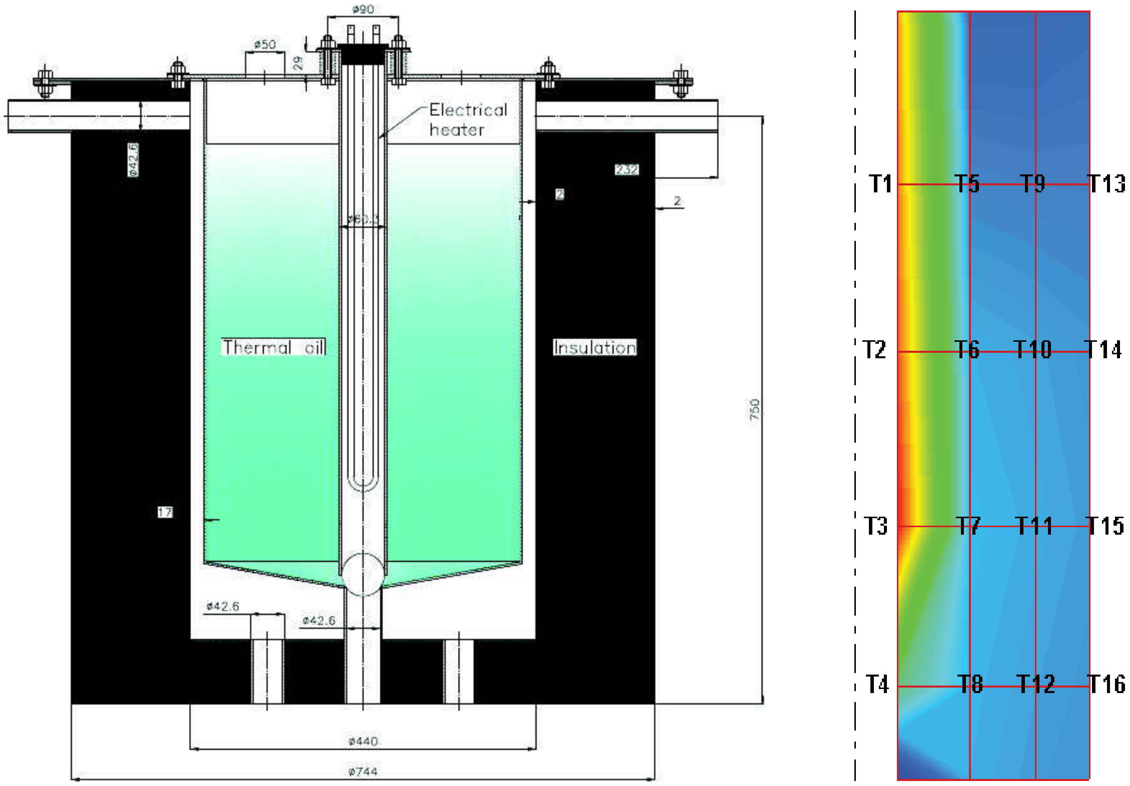
To distinguish the paraffin and thermal oil contribution to the overall heat storage capacity, it was necessary to make experiments on prototype filled solely with thermal oil. It was performed in old prototype (without additional cylinders filled with paraffin), where paraffin was replaced with thermal oil. The results thus obtained not only served for the analysis of the combined TST, but enabled insight in the characteristics of sensible TST with thermal oil as well. The final set of experiments was performed on new TST prototype, with paraffin inside cylinders, and thermal oil around it.

Final part of the work was development of numerical model of the processes in TST, in order to obtain an efficient tool for analysis of various geometries and working media combinations. The results obtained in the experimental part of the work were used to verify the model and to correct it, if necessary.
For the purpose of numerical modeling a Fluent 14.5 CFD package has been chosen.

2 Experimental setup

For conducting the experiments only with thermal oil the experimental facility that has been already served for the experiments with paraffin was used. was designed and built at the Laboratory for Thermal Engineering and Energy of the Institute of Nuclear sciences “Vinča”. Its shape and dimensions are presented at Figure 1. a). The main part is cylindrically shaped tank of about 77 dm^3. Heat storage media is heated by 2.4 kW electric heater, put in the inner cylinder, concentrically positioned at the axis of the main tank, and filled with sand, in order to increase thermal inertia of the heater and achieve uniform temperature distribution along the heater. Inside the heater there is a thermocouple, which enables the control of the heater temperature. If the temperature of the heater reaches the top of the given temperature range the electricity is switched off, until the temperature drops below the given range. Tank is filled from above, and emptied at the bottom of the cylinder. Tank is put in another concentric cylinder. Storage media is cooled by the air, which enters at the bottom, passes between the tank and the above mentioned cylinder, cooling the mantle of the tank, and goes outside through four tubes positioned with 90° to each other. Finally, outside the largest cylinder there is an insulation mantle.
For the measurement of temperature profile 16 thermocouples were placed inside the tank, four along the axis and four along the radius. Their enumeration was shown on Fig. 1. b). Beside the temperature measurement inside the tank it was necessary to measure the temperature of air at the entrance and at the exit of the tank. For temperature acquisition Kittley was used. The frequency of the stored temperature values

was 60 s, which was precise enough for the relatively small change of the temperature field inside the tank. For the measurement of the air flow rate a calibrated orifice was used. For the measurement of the dynamic and static air pressure difference a Alnor AXD 560 micromanometer was used.

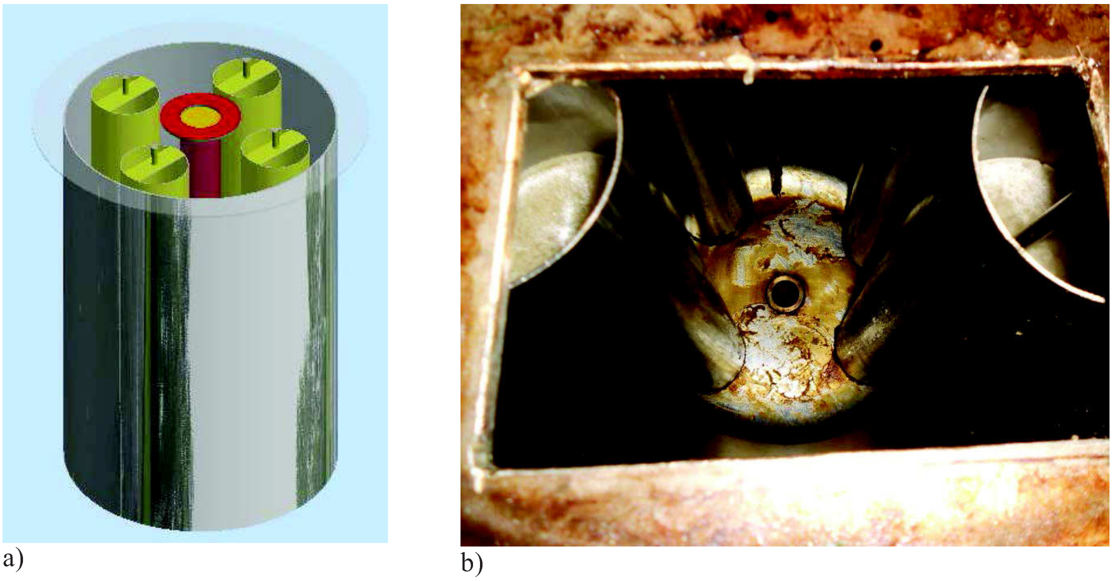


a)

b)

Fig.1. a) Sketch of the experimental setup for thermal oil; b) position and enumeration of thermocouples in this setup

For conducting experiments with simultaneous use of thermal oil and paraffin four additional cylindrical tanks were added in the inner space of the original tank, attached with the screw to the top of the tank, and filled with paraffin. Their position and shape could be clearly seen on Figs. 2.a) and 2.b), where the 3-D sketch and the photography of the inner space of the tank were correspondingly presented. Their total volume was about 19 dm^3, i.e. about 25% of the tank volume. Cylinders could not be filled up to the top, due to the paraffin spreading during heating. Thermal oil was filled up to the same height as paraffin. For measuring the temperature profile in paraffin four thermocouples were equidistantly placed along the axis of one of cylinders. Temperature profiles in the other three were assumed identical, since they were symmetrically placed around the heater.



a)

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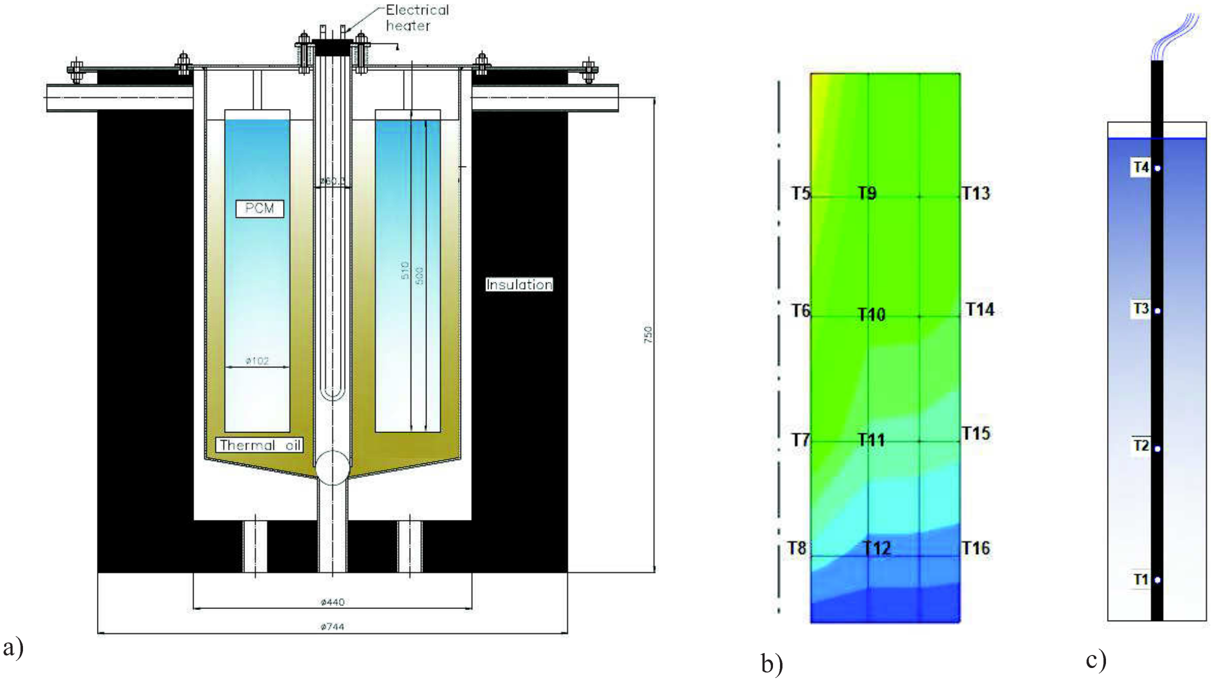
Fig.2. a) 3-D sketch of thermal oil – paraffin experimental setup; b) photography of the inner space of the tank

Due to the relatively small diameter of cylinders paraffin temperature radial profile was uniform, and it was not necessary to measure it. Since measuring device Kittley could not simultaneously measure more than 20 temperature values, number of thermocouples in thermal oil had to be reduced to12. The sketch of the whole experimental setup, together with the position of thermocouples and its enumeration were presented in Figs. 3.a) and 3.b).



a)

b)

c)

Fig.3. a) Sketch of the experimental setup for thermal oil-paraffin; b) position and enumeration of thermocouples in thermal oil; c) position and enumeration of thermocouples in paraffin.

3 Experimental results

3.1 Thermal oil

Measurements were performed during the thermal oil heating (heater turned on, no air cooling), during simultaneous heating and cooling (heater turned on, air cooling), and during the thermal oil cooling (heater turned off, air cooling). Heating power was regulated by defining the maximal temperature that heater could reach. For the performed measurements that temperature was 350°C (this temperature was inside the cylinder with the heater. It was experimentally found that the temperature of thermal oil close to the cylinder was still not high enough for thermal oil evaporation to happen.). During one regime the average heater power was kept constant. By changing the air flow it was possible to establish different stationary regimes.

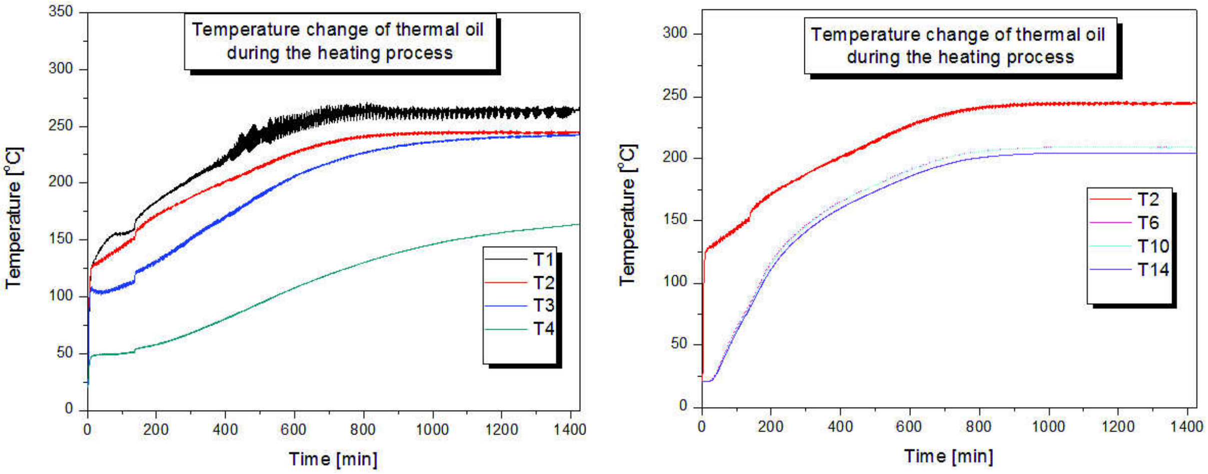


Fig.4. Temperature change close to the heater (left) and radial temperature profile at the referent level (right) during the heating period (900 W).

On Fig.4 axial and radial temperature profiles of thermal oil in relevant positions were presented. It could be seen that the temperature in the upper part of the tank uniformly rises along the axis.

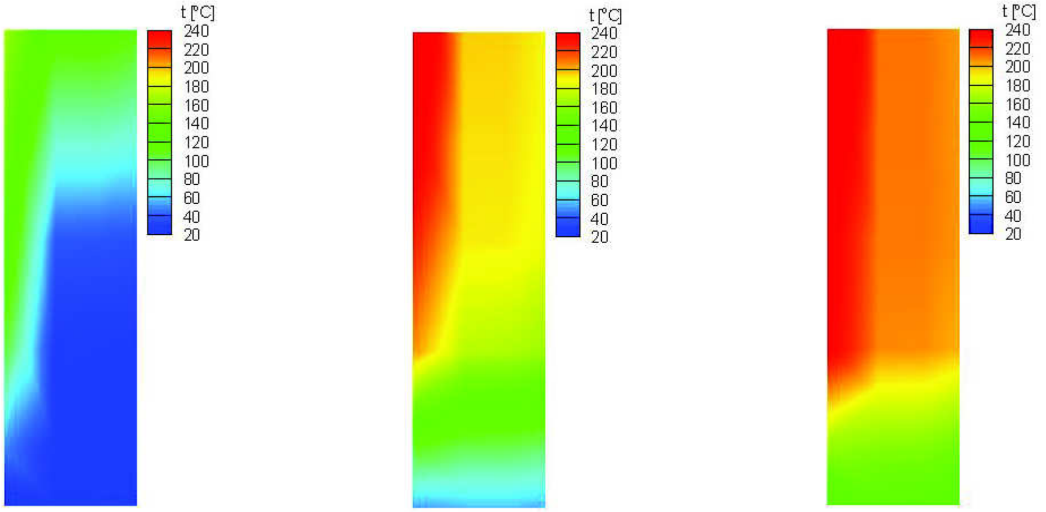


Fig.5. Thermal oil temperature profiles in the tank after: 60 min (left); 600 min (middle); the whole heating period of 1400 min (right) (heating power 900 W).

Near the bottom of the tank temperature is lower, since the heater length was about 400 mm and did not reach the lowest part of the tank. Closer inspection of the temperature values shows their zigzag change. This is due to the fact that the heater was periodically turned on and off (when it reached the temperature of 350°C) every 60-120 s, so that its average heating power was 900 W (nominal power of the heater was 2400 W).

For the better insight of the thermal oil temperature inside the tank, its profiles in the half of the vertical cross-section of the tank (heater is on the left edge of the profiles) after the 60, 600 and 1400 min of heating was given on Fig 5.

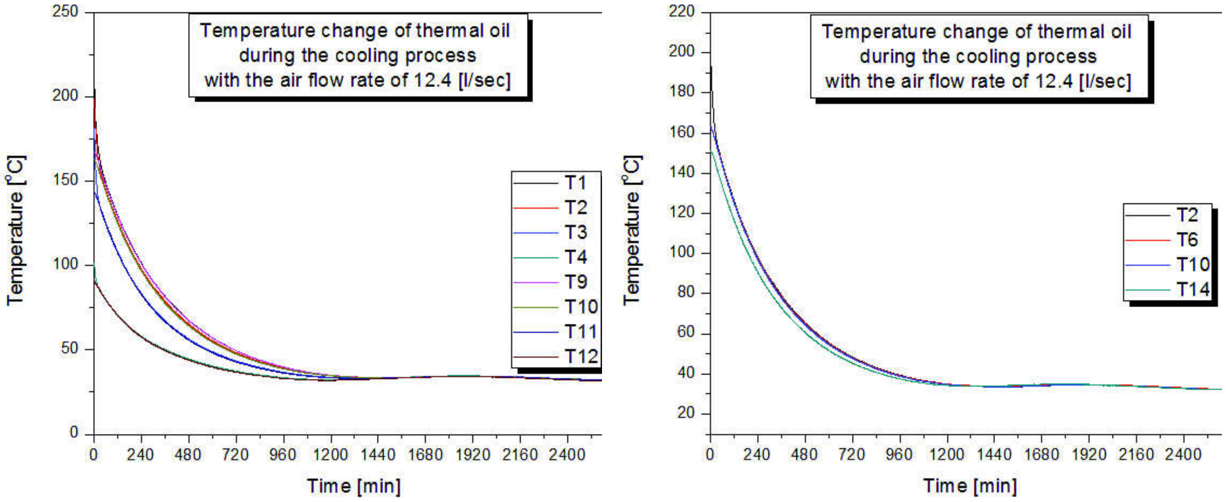


Fig.6. Temperature change close to the heater (left) and radial temperature profile at the referent level (right) during the cooling period.

After the heating period of 1400 min the heater was turned off and at the same time the air fan was turned on. Various experiments with different air flow rate were performed. For the flow rate of 12.4 l/s (somewhere in the middle of the flow range) the axial and radial temperature profiles in relevant positions during cooling period were presented on Fig. 6.

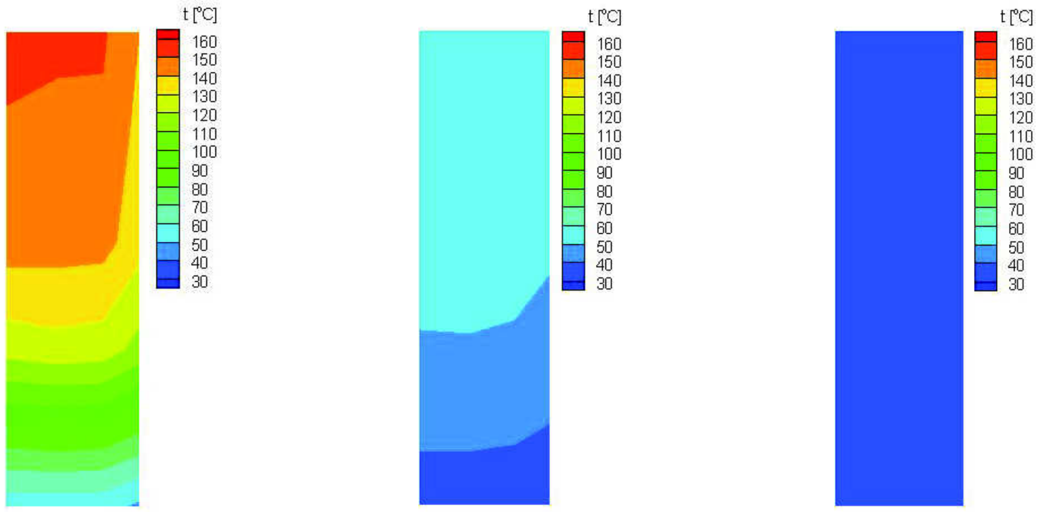
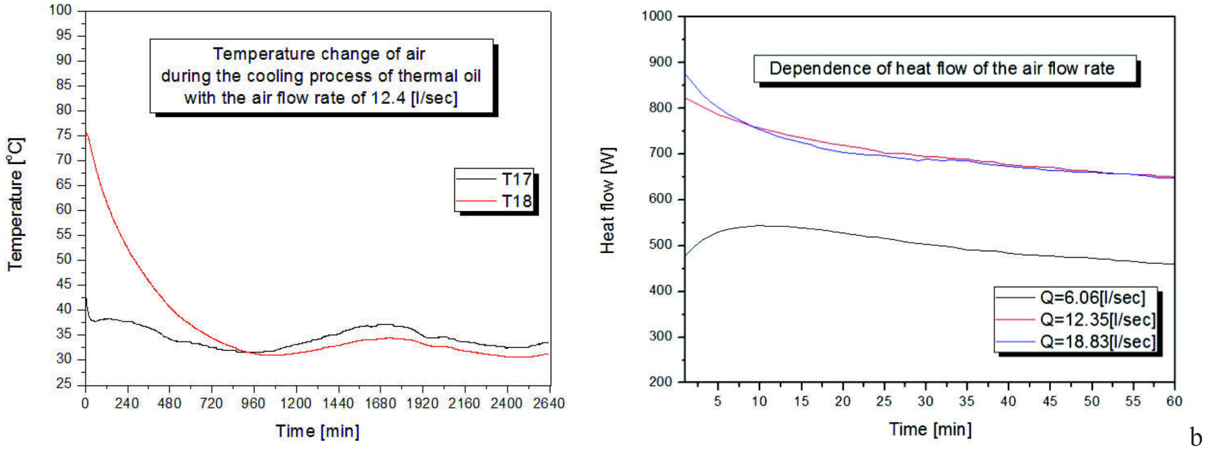


Fig.7. Thermal oil temperature profiles in the tank after: 60 min (left); 600 min (middle); the whole cooling period of 1400 min (right)

Thermal oil temperature profiles in the half of the tank vertical cross section after 60, 600 and 1400 min of cooling were presented on Fig. 7 (heater is on the left edge of the profiles.

The thermal oil was cool after about 15h. It is also clearly visible on both Figures 6 and 7 that that the radial temperature profiles after about 600 min are uniform, much more than in the case of heating. It could be explained by the fact that air for cooling flows around the tank mantle, i.e. that the cooling surface (the tank mantle) is much bigger than the heating surface (the surface of the cylinder where the heater was placed).



b

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a)

Fig.8. Temperature change of the air at the inlet and at the outlet of the experimental facility a) and dependence of heat flow of the air flow rate

The change of temperature values of air at the inlet and at the outlet of the experimental facility and the cooling intensity were presented on Fig. 8. Relatively high temperature of the air at the inlet is due to the fact that the same air serves to cool the engine of the fan, before it enters the experimental facility. Since the measurements of one cooling regime were performed during more than one day, the air inlet temperature varied, depending on the part of the day. It is also clearly visible that the cooling stops after 960 min.

Third set of the experiment with the pure thermal oil represent simultaneous heating and cooling. Figures 9-11 represent axial and radial temperature profiles for three different air flow rates. Zigzag pattern is again due to periodically turning on and off of the heater.

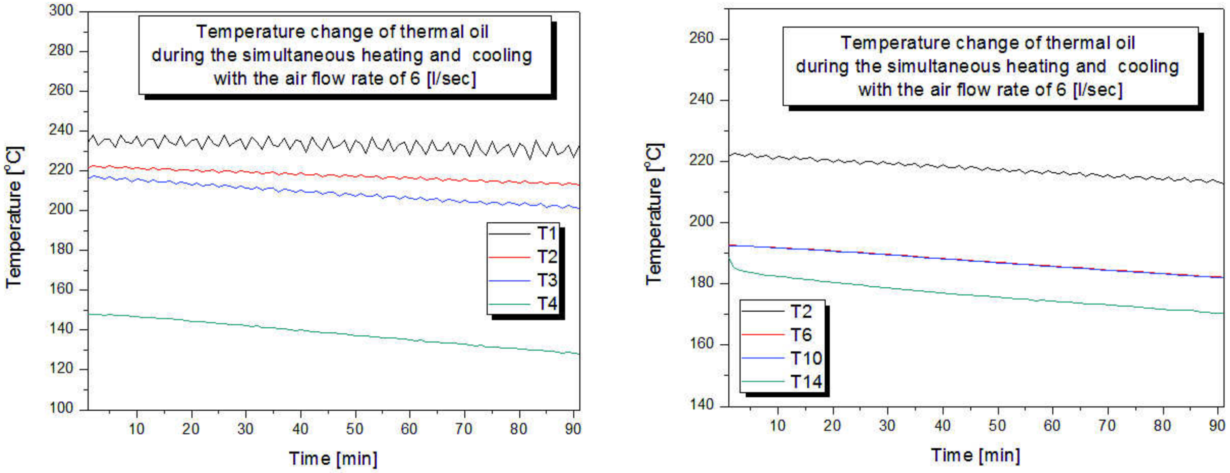


Fig.9. Temperature change close to the heater (left) and radial temperature profile at the referent level (right) during the simultaneous heating and cooling (air flow rate 6 l/s, heating power 900 W).

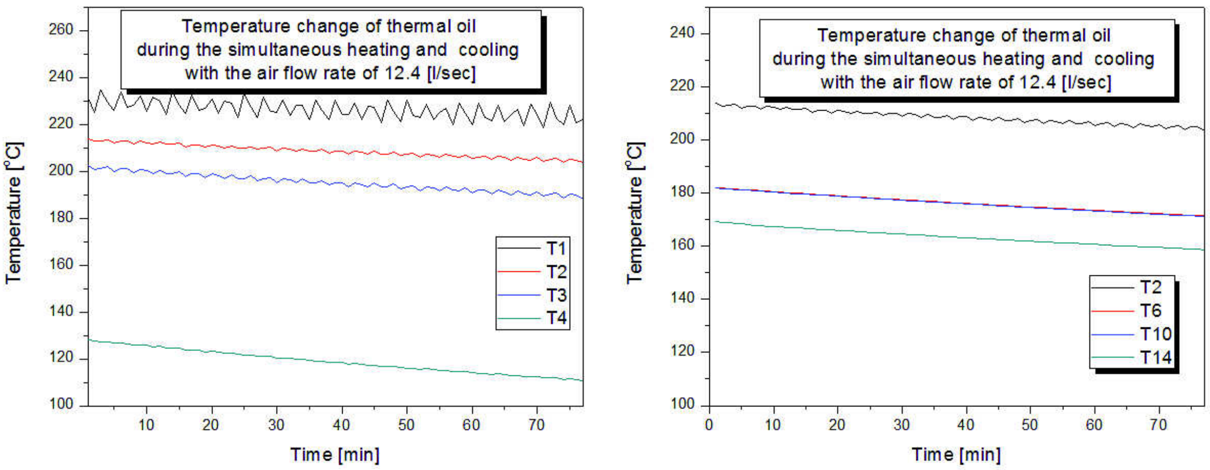


Fig.10. Temperature change close to the heater (left) and radial temperature profile at the referent level (right) during the simultaneous heating and cooling (air flow rate 12.4 l/s, heating power 900 W).

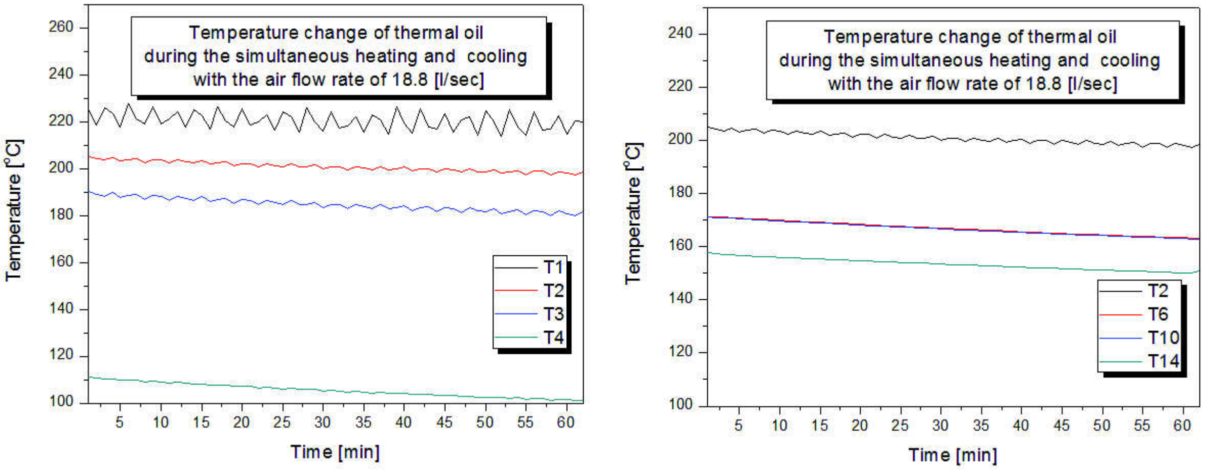


Fig.11. Temperature change close to the heater (left) and radial temperature profile at the referent level (right) during the simultaneous heating and cooling (air flow rate 18.8 l/s, heating power 900 W).

Since the slope of the temperature drop was in all cases almost the same, it can be concluded that in the presented range the air flow rate does not influence the cooling intensity significantly.

3.2 Thermal oil –paraffin

As in the case of thermal oil, measurements were performed during heating, during cooling and during simultaneous heating and cooling. On Fig. 12 axial and radial profiles of thermal oil during heating were presented. Comparing radial profile of thermal oil with that obtained during heating of pure thermal oil (Fig. 4), a much bigger temperature difference between regions close to the heater and close to the wall was here obtained. This can be explained by transferring a large amount of heat to paraffin, which was necessary for its melting.

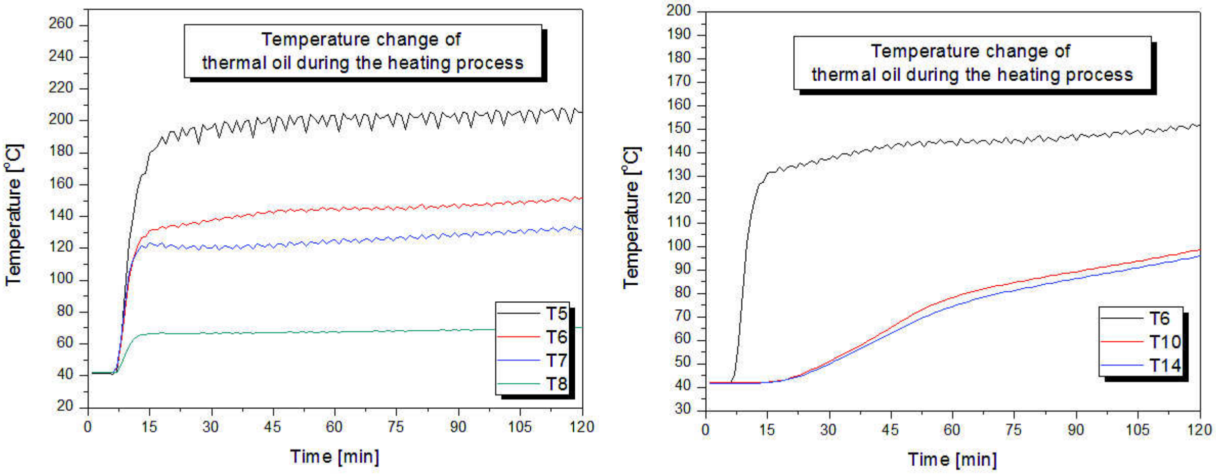


Fig.12. Axial profile close to the heater (left) and radial profile (right) of thermal oil during heating

On Fig.13 a paraffin temperature profiles during the first 120 min and 300 min of heating were presented. It is clearly visible that the paraffin first melts in the upper part of the cylinder, due to the higher temperature of thermal oil around that zone. An abrupt temperature drop in that zone after about 130 min was obviously caused

by paraffin evaporation on the surface of the cylinder. It is also interesting to note that after about 230 min the temperature in cylinder becomes uniform, which is the result of vertical circulation of liquid paraffin, caused by the existence of paraffin vertical density gradient.

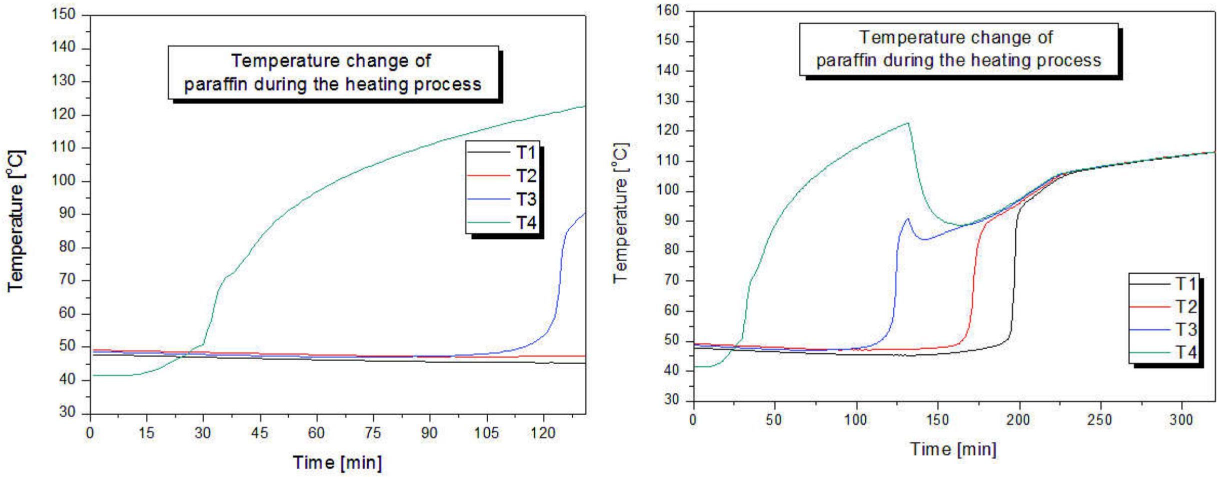


Fig.13. Paraffin temperature profile during the first 120 min (left) and 300 min (right) of heating

On Fig.14 vertical temperature profiles in thermal oil close to the heater and in paraffin during free cooling were presented. Heater and air fan were turned off, so the energy loss was occurring through the top cover of the facility, which was not isolated. It is interesting to note that the slope of the paraffin temperature is almost horizontal at about 60 °C, which was obviously affected by the phase change.

The last set of experiments was performed during simultaneous heating and cooling, i.e. both heater and air fan were turned on. The air flow rate was changing, in order to find out the dependence of air velocity on heat transfer. Since the obtained data set was very comprehensive, it was not possible to show all the results in this work. Therefore, only vertical temperature profile of thermal oil close to the heater and of paraffin in the first 60 min of the mentioned regime and for characteristic flow of 9 lit/s was presented on Fig 15.

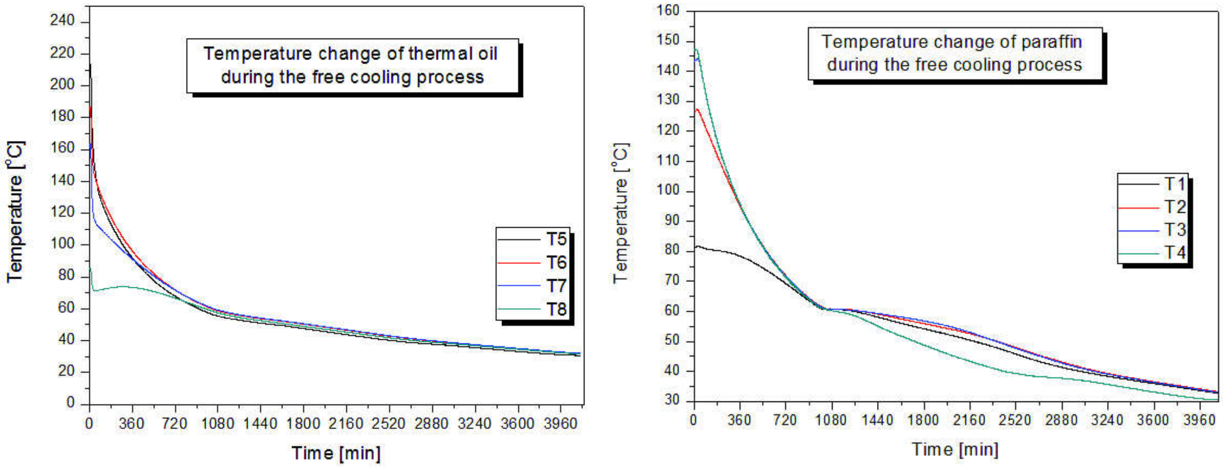


Fig.14. Thermal oil temperature profile close to the heater (left) and paraffin temperature profile (right) during cooling

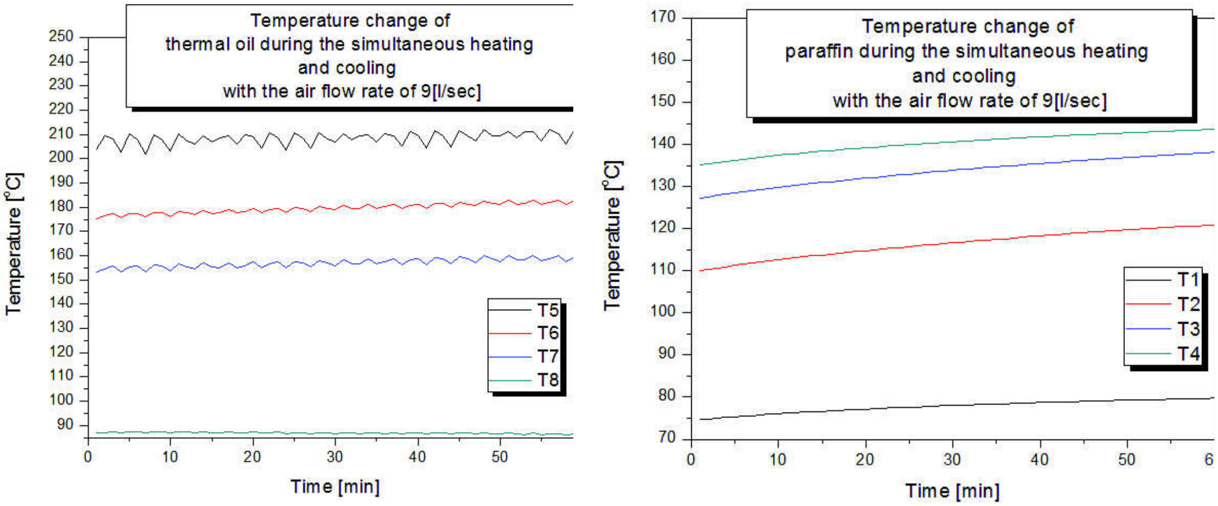


Fig.15. Thermal oil temperature profile close to the heater (left) and paraffin temperature profile (right) during simultaneous heating and cooling

4. Numerical results

For the development of the numerical model of heat transfer and fluid flow processes in TST a commercial numerical package Fluent 12.1 was used, since it possesses its own routine for computation a temperature and flow fields in TST with the change of phases, but also it allows to user to implement the package with its own model by using the user define functions.

Due to the presence of cylinders with paraffin the geometry was not symmetrical in the radial direction. Therefore, it was necessary to perform a 3-D numerical simulation. The numerical grid of only one fourth of the tank was generated, since all of them are identical. Geometry of the calculated flow field was presented on Fig 16.

The number of control volumes for the given geometry was 629,000. For the actual size of the tank it was quite enough for obtaining reliable numerical results. The whole domain was divided on several domains. Numerical grid was generated in every domain separately. On this way it was easier to control the size of control volumes in the regions where it was crucial for obtaining convergence, and it was also possible to define different boundary conditions on different domains. Heat was entering the domain through the inner radial side of the domain, which simulated the electrical heater. Heat losses were only through the upper boundary of the domain. There were no heat losses through the side boundaries, due to the symmetry of the whole facility.

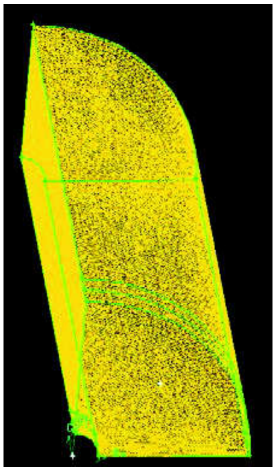
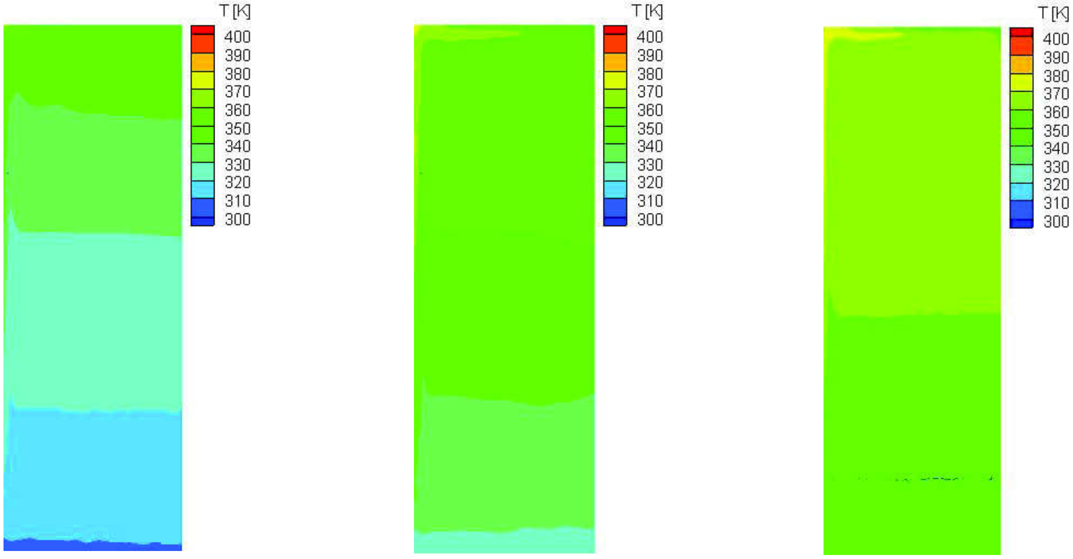


Fig16.

In this work the results of thermal oil heating were only presented. That means that in the numerical simulation instead of paraffin cylinders were also filled with thermal oil. Temperature profiles in the vertical cross section of the tank after 60, 120 and 180 min were presented on Fig.17. The position of the heater induces higher temperatures in the upper part of the tank (although the temperature losses are only through the top of the tank. At the beginning the vertical temperature gradient is bigger, but later the profiles become more uniform, which can be explained by more intense vertical circulation, induced by the difference in density between the hotter and cooler thermal oil.



60 min 120 min 180 min

Fig.17. Vertical temperature profiles of thermal oil after 60, 120 and 180 min of heating

5. Conclusion

A part of the results obtained from measurements on the laboratory experimental TST setup and from the numerical simulation with thermal oil as the working material that fills the whole tank and with the cylinders of paraffin submerged into the thermal oil was presented. They represent the result of the continuation of the activities on the project with the aim of obtaining a detailed insight of processes in TST, through collecting a comprehensive set of experimental data and results from numerical simulation. Measurements were performed in transient regimes of heating and cooling, and in the regimes with heating and induced cooling with air simultaneously, as well as in the regimes of natural cooling only. They were also performed for different mass flow rates of the cooling air. For the temperature profile detection a grid of 16 thermocouples was placed inside the tank. The analysis of the obtained results showed that this number of thermocouples was enough for getting the reliable insight of temperature distribution inside the tank.

The idea to put cylinders of paraffin in the tank that is filled with thermal oil results from the analysis of previous experiments with paraffin as the only working material that fills the whole volume of the tank. They showed that the central position of heater cause the intense heating and even evaporation of paraffin. It was necessary to remove the paraffin from that region of intense heating and to use thermal oil both as the working material that stores energy and as a kind of interface between the heater and paraffin. The ratio of the volume of thermal oil and paraffin in the experimental facility was 3:1, while in the real facility it could be even opposite.

During the experiments thermal oil was confirmed as appropriate and reliable working media. Although it does not change the phase and that its latent heat could not be used for storing energy, the fact that it stays liquid enables inserting some kind of turbine into the tank to induce forced circulation of thermal oil. That is, the results showed that the lower part of the facility was heated much slower than the upper part, and the natural circulation is too weak to enable uniform temperature in the whole tank (in the experimental facility the length of the heater was 400 mm, two thirds of the height of the tank, and in the real TST the energy source could be much smaller in size, with even less uniform temperature profile as consequence). Creating the uniform temperature profile of thermal oil with its induced circulation would enable more uniform heating of some other working material (that can change the phase, and whose latent heat could be used for energy storing) that fills the inner cylinders. On this way the capacity of TST could be significantly enlarged, especially if inner cylinders occupy larger amount of the TST volume.

Analysis of the numerical results shows that the heating of thermal oil in numerical simulation is slower than in experiments. The probable reason is inadequate boundary conditions at the top of the computational domain (the unreliable assumptions in the model of natural convection). In the future numerical work a special attention will be devoted to solve that problem, before the more complex numerical simulation with couple of working materials with phase change is being undertaken.

The emphasis of the future work will be on:

- Finding a suitable working material that changes phase at higher temperatures and experimenting with it, and consequently the other interface liquid (instead of thermal oil) that does not evaporate nor disintegrate on these temperatures.
- Changing the way of cooling in the existing facility. One possibility would be to insert a circular pipeline into the tank, with thermal oil as the cooling media. This will certainly improve the heat exchange significantly.

ACKNOWLEDGMENT

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