EKSPERIMENTALNO ISTRAŽIVANJE TERMIČKIH PROCESA U AKUMULATORU TOPLOTE SA PROMENOM FAZE

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EXPERIMENTAL RESEARCH OF THERMAL PROCESSES IN THE THERMAL STORAGE TANK WITH A PHASE CHANGE MEDIUM

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ABSTRACT

Instaliranje akumulatora toplote (AT) u postrojenja koja koriste obnovljive izvore energije predstavljaju dobar način da se poveća njigova energetska efikasnost. Ovaj rad opisuje deo aktivnosti (obavljenih tokom realizacije druge godine projekta III 42011 koji finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije) na razvoju AT kod kojih se materijal za akumulaciju topi na atmosferskom pritisku, omogućavajući na taj način korišćenje energije faznog prelaza za skladištenje energije. AT ovog tipa omogućavaju veću količinu akumulirane toplote po jedinici zapremine, a takođe omogućavaju (u zavisnosti od radnog medijuma) dostizanje viših temperatura radnog medijuma, što je neophodan uslov kod postrojenja sa kogeneracijom. U svrhu eksperimentalnog ispitivanja strujnih i termičkih procesa u AT, u Laboratoriji za termotehniku i energetiku Instituta za nuklearne nauke “Vinča” konstruisan je i izrađen prototip takvog AT. On je cilindričnog oblika, zapremine 77 dm^3. Radni material se grejao električnim grejačem snage 2,4 kW, postavljenog u osi AT, a hladio se vazduhom koji je strujao oko AT. Merenje temperature u AT se vršilo pomoću 16 termoparova, postavljenih u rešetku, 4 po visini i 4 duž poluprečnika AT. U svrhu ovog rada kao radni medijum izabran je paraffin. Merenja su vršena kako u nestacionarnom tako i u stacionarnom režimu rada. Dobijena je obimna baza eksperimentalnih podataka, koji će se u daljnjoj realizaciji projekta koristiti u numeričkom istraživanju, za razvoj modela, verifikovanje njegovih rezultata, i ukoliko je potrebno, za njegovu korekciju.

Ključne reči: akumulator toplote, merenja, paraffin, promena faze

Introduction of thermal storage tanks (TST) in facilities that use renewable energy resources represents a good way to increase their energy efficiency. This paper surveys a part of the activities (performed during the realization of the second 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. TST of this type enable more thermal energy storage per volume unit, but also (depending of the working medium) enable higher temperatures of the working medium, which is necessary in the co-generated facilities. For the purpose of the experimental research of thermal and flow processes in TST in the Laboratory for thermal engineering and energy of the Vinča Institute a prototype of TST was designed and made. It has a cylindrical shape, with the working volume of 77 dm3. The working material is heated by 2.4 kW electric heater positioned along the TST axes, and is cooled by the air which circulates around the tank. The measurement of temperature inside the tank was performed by 16 thermocouples, 4 along the tanks height and 4 along the tanks radius. For the purpose of this work paraffin as a working medium was used. Measurements were performed for non-stationary as well as for stationary working regimes. As a result, an extensive set of experimental data was obtained, which, in the later work on the project, will serve in the numerical study, as a basis for the developing a numerical model, to verify its results and, if necessary, to correct the model.

Key words: energy storage tank, measurements, paraffin, phase change

1. INTRODUCTION

It is difficult to imagine an optimized facility that uses one of the renewable energy resources like biomass, solar energy etc. that does not comprises at least one thermal storage tank (TST). Moreover, TST represents an essential part in the optimization of such systems. 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. Consequently, 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 thermophysical, 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.

To perform numerical research, i.e. to develop numerical model with the chosen CFD package properly, to verify its results and, if necessary, to correct the model, a comprehensive set of experimental data of the heat storage medium parameters in TST as well as data of the heat exchange process has to be supplied. This paper restricted itself only on that experimental part of the complex experimental-numerical research.

2. EXPERIMENTAL SETUP

An pilot facility 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. The thermal power of the heater is regulated by changing the voltage. 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.

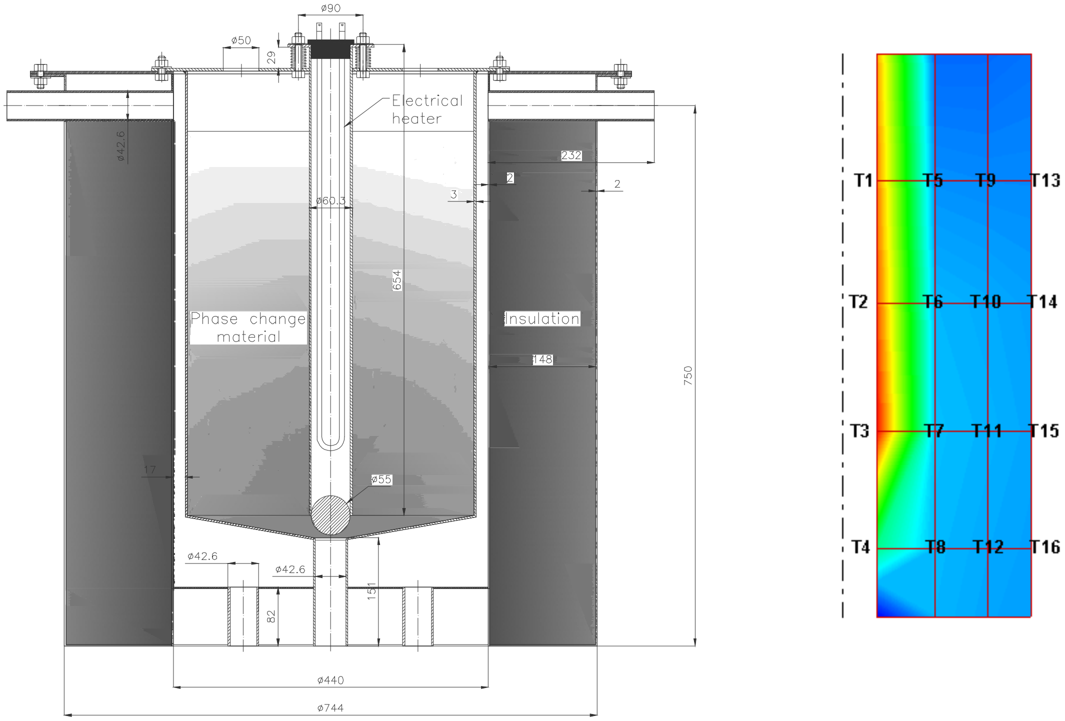

Fig. 1. a) Sketch of the experimental setup; b) position of thermocouples in the setup

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 Fluke 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 Alnor AXD 560 micro manometer was used.

3. EXPERIMENTAL RESULTS

Measurements were performed during the paraffin heating (heater turned on, no air cooling), in the stationary regime (heater turned on, air cooling), and during the paraffin cooling (heater turned off, air cooling). It was possible to change the power of the heater by changing the voltage. Original power of the heater (for voltage of 220 V) was 2.4 kW. Except this one, measurements were performed for two other heater powers: 0.8 kW (125 V) and 0.5 kW (100 V). During one regime the heater power was kept constant. By changing the air flow it was possible to establish different stationary regimes.

Figs. 2-4 describe heating regime for the heater power of 2.4 kW. It could be seen that along the tank axis close to the heater paraffin melts and reaches relatively high temperature quickly. In the radial direction (Fig. 3.) temperature rises more slowly, and melting starts much later. Sudden drop of the temperature was detected at the region close to the heater, approximately 200 minutes after the beginning of the heating process. Authors are still not quite certain what actually happened. One possible explanation is that the paraffin close to the heater reached the boiling temperature and started to evaporate, causing the sudden loss of the considerable amount of energy.

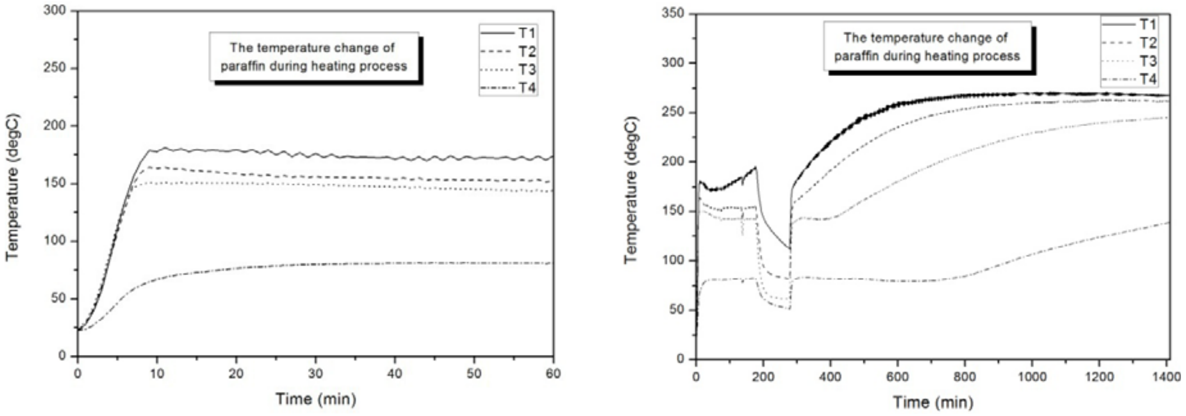

Fig. 2. Temperature change close to the heater (2.4 kW) during: first 60 min (left); the whole heating period (right)

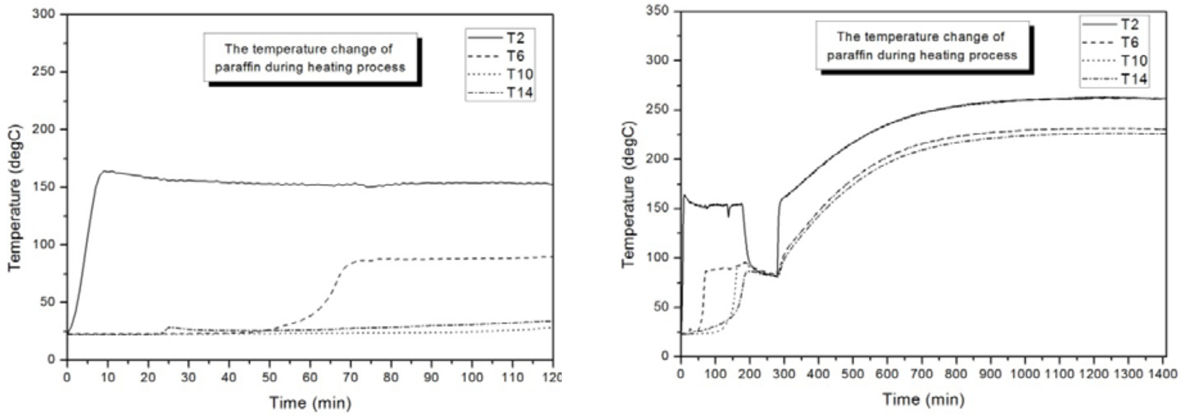

Fig. 3. Radial temperature change at the referent level during: first 120 min (left);

the whole heating period (right) (heating power 2.4 kW)

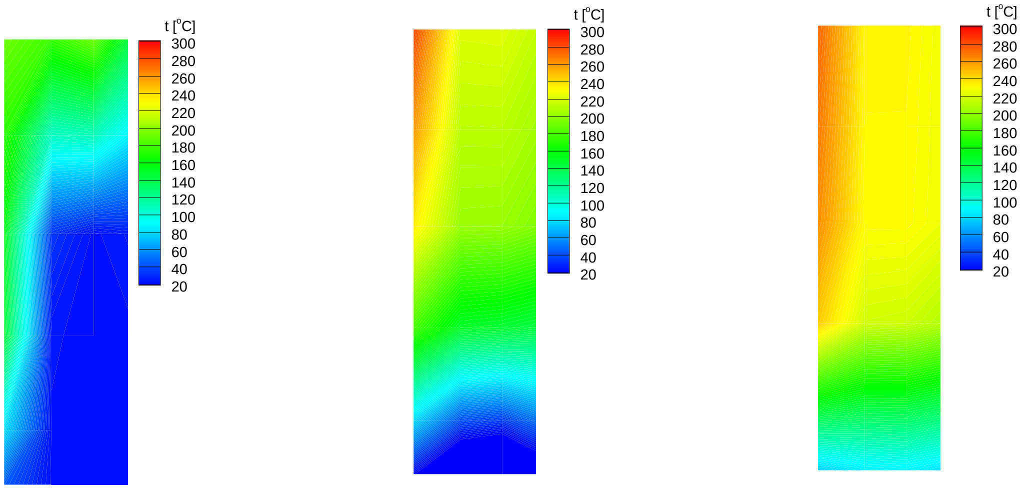

Fig. 4. Paraffin temperature profiles in the tank after: 60 min (left); 600 min (middle); the whole heating period of 1400 min (right) (heating power 2.4 kW)

Fig. 5. describes temperature change along the axis and in the radial direction during the paraffin cooling (heater turned off). It could be seen (especially on Fig. 7) that the temperature profile inside the tank is much more uniform than in the heating regime. The reason is uniform distribution of air at the bottom of the tank. Also, the zones close to the wall were cooled faster, due to the fact that air flows along the tank wall. Temperatures of the air at the inlet and at the exit was shown on Fig. 6. Temperature of the air jumps suddenly at the beginning of the cooling regime, and then gradually drops, finally reaching the air temperature at the inlet, at the moment when temperature of the paraffin drops to the value of the air temperature at the inlet, and when there were no more cooling by the air.

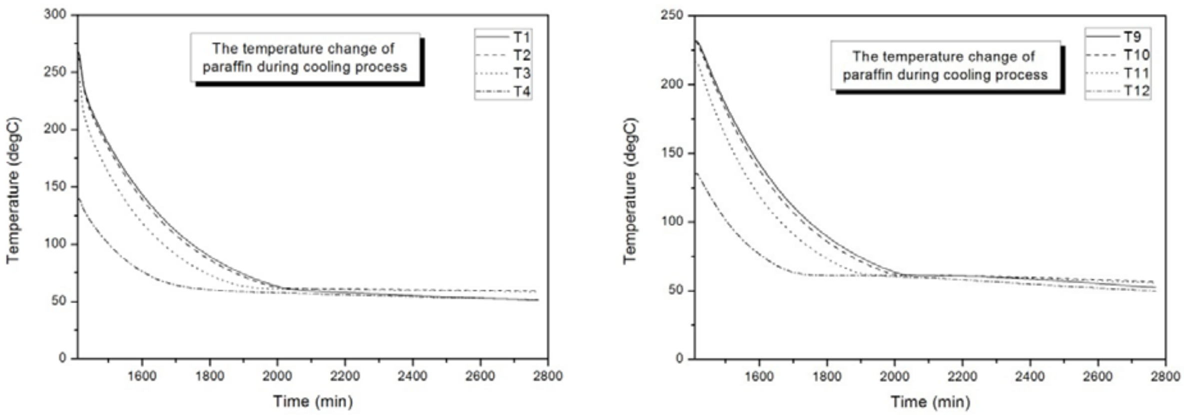

Fig. 5. Temperature change close to the heater (2.4 kW) during the cooling period: close to the heater (left); close to the tank wall (right)

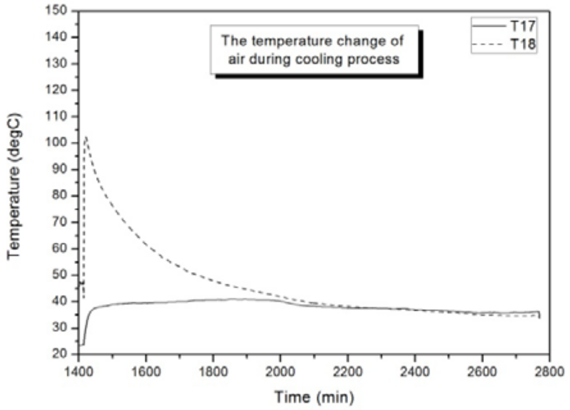

Fig. 6. Temperature change of air during the whole cooling process (2.4 kW)

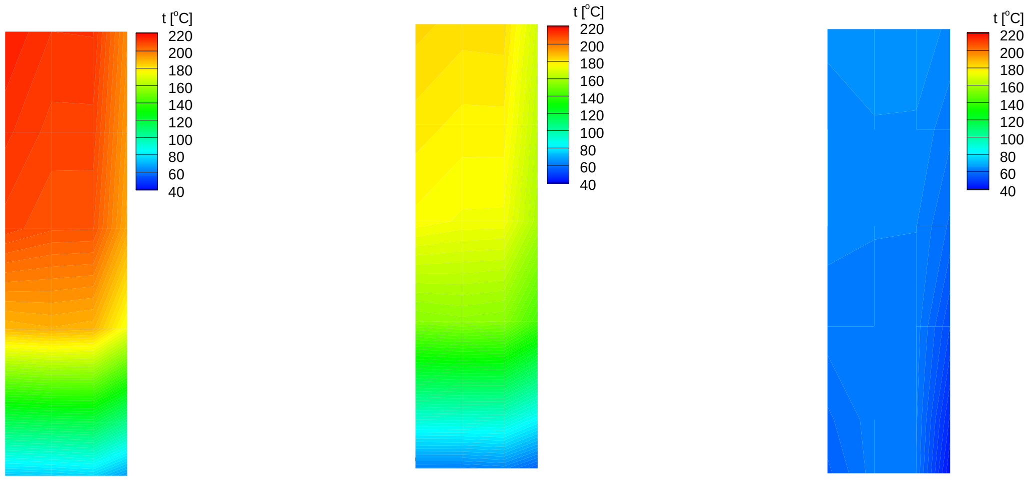

Fig. 7.Paraffin temperature profiles in the tank after: 60 min (left);

120 min (middle); 600 min (right) (cooling) (2.4 kW)

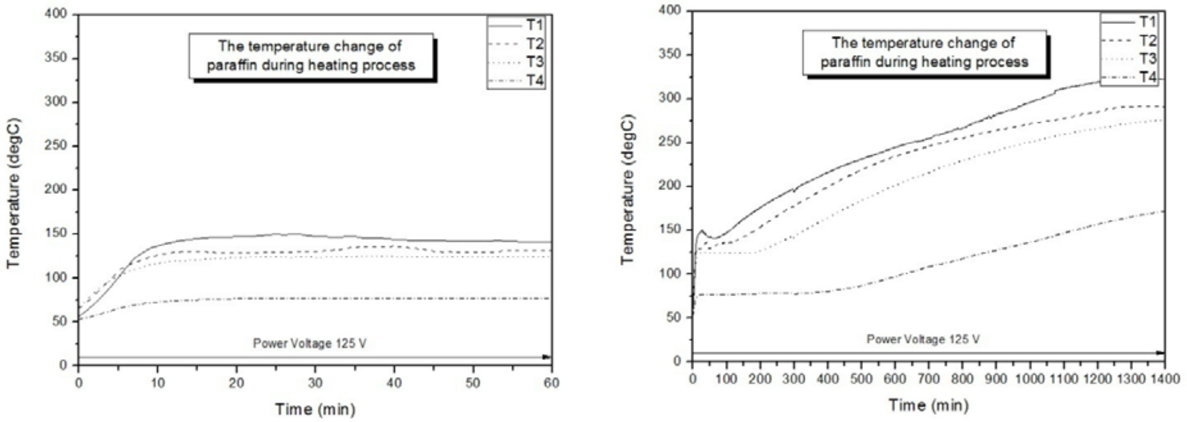

Fig. 8. Temperature change close to the heater (0.8 kW) during: first 60 min (left);

the whole heating period (right)

Figs. 8-10 describe the heating regime for the heater power of 0.8 kW. Also here, in the regions close to the heater the paraffin temperature rises quickly, almost to the same value as for the previous case, but in the rest of the tank temperature rises much slowly and much uniformly. Obviously, there was enough time for considerable amount of heat to pass to the regions closer to the wall before the regions close to the heater reached high temperatures.

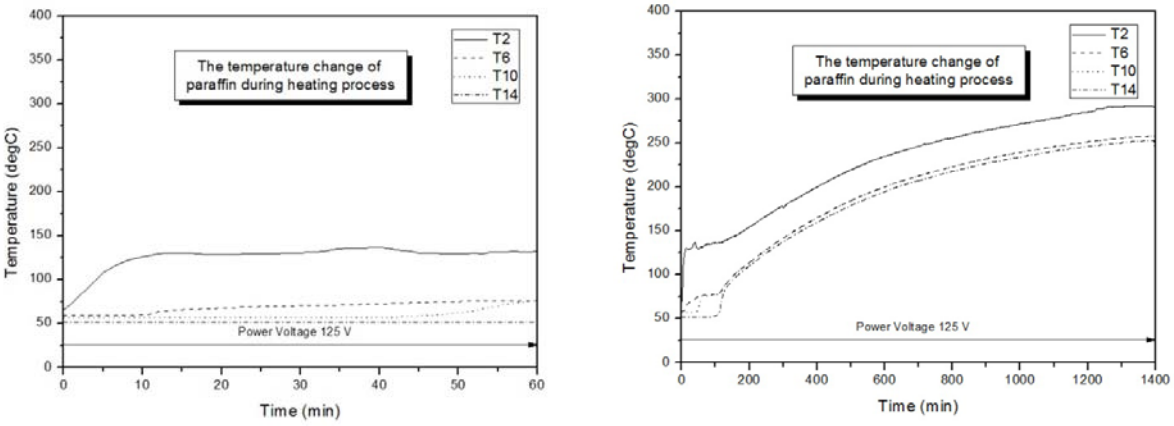

Fig. 9. Radial temperature change at the referent level during: first 60 min (left); the whole heating period (right) (heating power 0.8 kW)

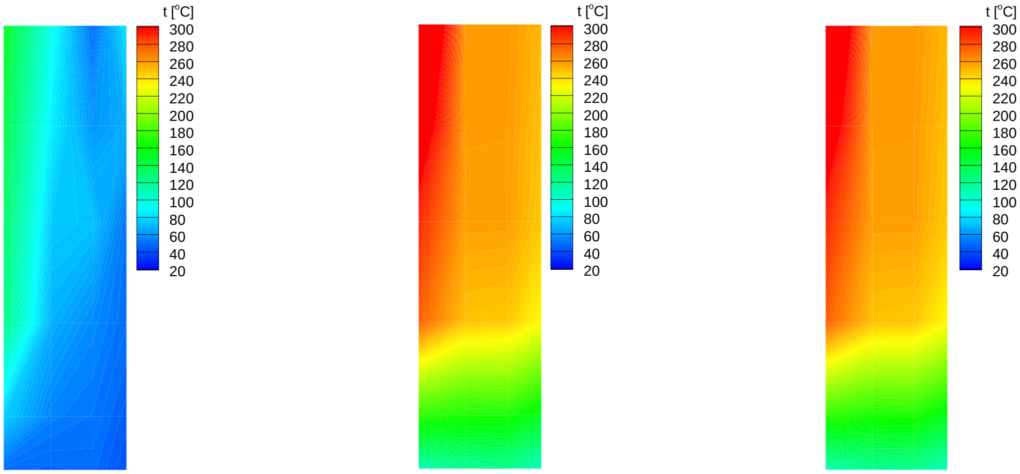

Fig. 10.Paraffin temperature profiles in the tank after: 60 min (left); 600 min (middle); 1400 min (right) (heating power 0.8 kW)

Left parts of the diagrams on Fig. 11. describe the transient regime after the cooling was switched on (heater has also been switched on), and right parts show the cooling regime for the heater power of 0.8 kW.

After the beginning of the cooling process, while heater is still switched on, after few hours, the system reaches steady-state. On Fig. 12 temperature difference of the air for different air flow rates was shown.

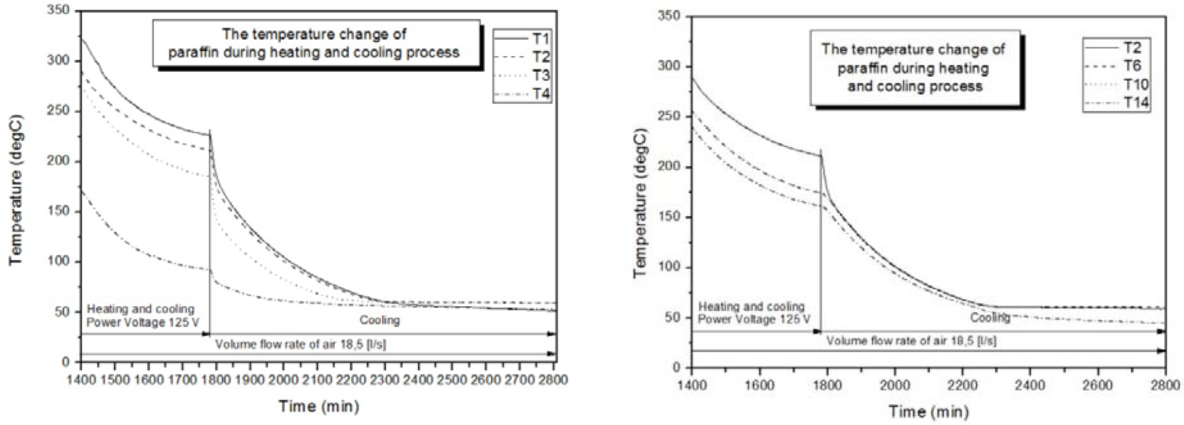

Fig. 11. Temperature change close to the heater (2.4 kW) during the cooling period: close to the heater (left); at the referent level (right) (0.8 kW)

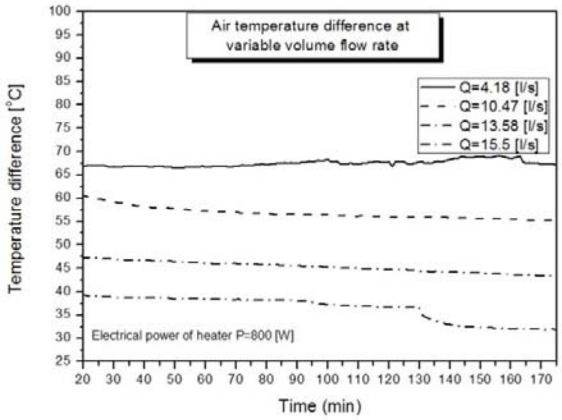

Fig. 12. Temperature difference of air during the cooling process for different air flow rates (0.8 kW)

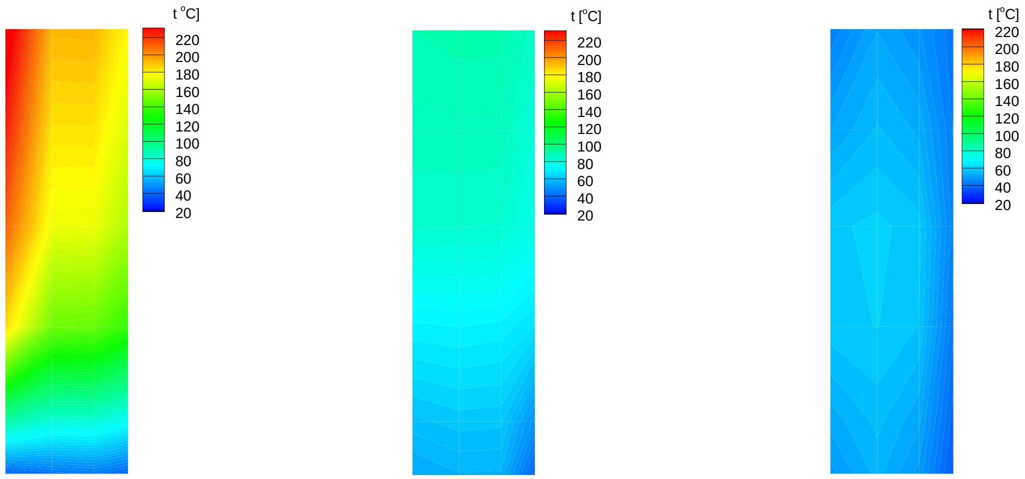

Fig. 13.Paraffin temperature profiles during cooling in the tank: at the beginning of cooling (left); after 320 min (middle); after 1000 min (right) (heating power 0.8 kW)

4. CONCLUSION

A part of the results obtained from measurements on the laboratory experimental TST setup with paraffin as the working material was presented. These measurements are the first part in the comprehensive experimental research, which will include other working materials, whose melting temperature is much higher than paraffin's. The experimental setup was so designed that it can fulfill the required task. Measurements were performed in transient regimes of heating and cooling, and in the stationary regimes with heating and cooling simultaneously. They were also performed for different heating power and 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.

In all measured regimes the temperature profile during heating was rather non-uniform. Close to the heater paraffin quickly reached high temperatures and even started to evaporate, while in the rest of the tank, due to the paraffin's low thermal conductivity it remained solid. On this way the heat storage capacity is reduced. This shows that the heat exchanger in the real facility with paraffin as the working material should not be placed in the center of the tank. It should be so designed that the regions close to the wall are heated simultaneously with the central regions. Still, it should not be placed too close to the wall. Such conclusion was obtained from the analysis of the results obtained in the regime of cooling. In the experimental facility paraffin was cooled by the air entering at the bottom and flowing around the tank walls. Although the temperature profile was much more uniform than in the heating regime, the lower part of the tank was cooled faster. Central parts of the tank remained warmer even after 24 hours of cooling.

Performed measurements obtained comprehensive set of data which should serve for the proper design of the real TST facility. One should have in mind that it is not sufficient by itself, due to the lack of capability to include all the characteristics of the real facility in the experimental setup. Rather, it should serve as a tool for testing the validity of the numerical model of TST, with which it will be possible to vary working parameters in a much wider range, to check various solutions, and find the optimal one. In the future work on the project it was planned to make such numerical model, and to perform numerical research, simultaneously with the continuation of performing experiments with other working materials and with the improvement of the TST setup.

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