Influence of Nanoparticles on the Processes of Heat Accumulation During Material Phase Transformations

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Abstract. Heat accumulators are widely used to store and further utilize heat energy from solar collectors, heat pumps and other renewable energy sources. In this case, materials with phase or chemical transformations may be used. This makes it possible to significantly increase the accumulation of heat energy per unit mass of the heat storage material compared to the batteries on solid and liquid materials. To increase the efficiency of materials with phase transformations, fillers are used in the form of nanoparticles having a high coefficient of thermal conductivity. This paper presents the results of numerical modeling and experimental study of the influence of nanoparticles on the processes of heat energy accumulation in paraffin. The influence of geometric dimensions, concentration and thermophysical characteristics of nanomaterials on the processes of heat energy accumulation during paraffin phase transformations is investigated. Thermophysical properties of composite materials were investigated by optical spectroscopy. In experimental and numerical studies, the dynamics of melting processes of accumulating material with nanoparticles near cylindrical heat sources have been studied. A comparative analysis of heat-accumulating materials in the presence and absence of nanoparticles was carried out.

Keywords: Heat transfer · Phase transformations · Heat-accumulating material · Nanoparticles · Numerical modeling · Optical spectroscopy methods

1 Introduction

The limitation of traditional fuel and energy resources (gaseous, liquid and solid fuels), as well as the negative impact of their combustion products on the environment, testify to the necessity of creation and practical using of combined power supply systems for consumers, including alternative one's sources of energy.

The problem of the transition from traditional to alternative sources of power supply for industrial consumers and housing or communal services has been researched in [1–3]. It is noted that the most universal for autonomous energy supply systems, in terms of energy potential and the possibility of its public use is solar power. However, as is known, the use of this energy is complicated by the stochastic nature of its receipt,

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which results in the need to ensure the continuity of these systems. The latter can be achieved both by incorporating traditional power sources into them and using different types of energy accumulators. Therefore, from all considered variants of schemes of power supply of consumers, the most interesting is the variant of complex energy supply of the consumer both from the external electrical network, and from the sources of solar energy with the possibility of accumulation of thermal and electrical energy.

Of all types of existing designs of heat accumulators, heat storage accumulators with phase or chemical transformations of accumulating material are the most promising. They allow to provide high density of accumulated energy and stable temperature at the exit from the heat accumulator.

A number of authors [4, 5] analyzed the different methods of heat accumulation, which showed that one of the promising directions is the use of heat accumulators of periodic action, based on phase or chemical transformations of accumulating material. In accumulators of this type there per unit of mass and a stable temperature of the coolant at the outlet of the heat accumulator. Detailed information on the processes of heat and mass transfer occurring during phase transformations of the accumulating material is given in sources [4–14]. The analysis of the conducted researches shows that in order to increase the efficiency of heat accumulators, it is necessary to intensify the processes of heat and mass transfer during "charge" and "discharge" of these accumulators, as well as to reduce heat losses when storing thermal energy [6–11]. One of the most important directions for improving efficiency of the heat accumulators based on the principle of phase transformation is to improve the thermal storage and conductivity properties of the heat-accumulating materials. This in turn achieved by using of nanoparticles [15–17]. But, notwithstanding this, a number of questions regarding the thermophysical properties, concentration, type and size of nanoparticles in the composite phase change material (PCM) remain insufficient investigated. Hence one can important to carry out numerical and experimental studies of heat accumulation processes in PCM contains a fillers in the form of nanoparticles with a high coefficient of thermal conductivity.

2 Analysis and Methodology

The system of complex energy supply of consumers from the energy of traditional and alternative sources with the use of electric and thermal accumulators is proposed. It is based on the use of solar energy and/or electrical power with the possibility of accumulation of its excess in accumulators of electric and thermal energy of the improved design. The application of this system is envisaged in places where the solar energy converters are the main source, and the electrical network is auxiliary. Figure 1 shows the functional diagram of the proposed system of integrated energy supply of consumers.

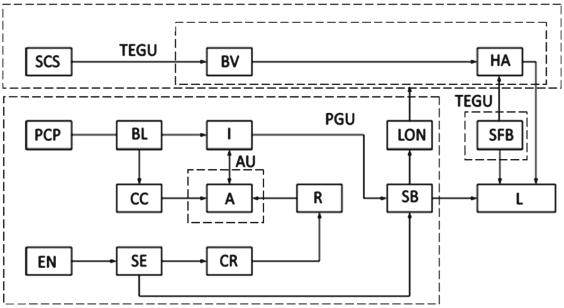


Fig. 1. Block diagram of the system of integrated energy supply of consumers with energy accumulators.

The system consists of three main units: PGU – power generation unit, AU – accumulator unit and TEGU – thermal energy generation unit, which includes: photovoltaic converter panels (PCP) that convert solar energy into electrical energy for load needs (L), the electrical network (EN), the connection of which occurs in periods when the energy generated by the PCP is not sufficient for the needs of L, at the conditions of full discharge of the accumulator unit (AU). The transformation of the voltage of the PCP from a constant to a variable is carried out using the inverter (I), the reverse – rectifier (R). When increasing the level of solar activity, in order to avoid recharge of accumulators, the system provides a controller of charge (CC) from photovoltaic converter panels and a charge regulator (CR) from the electrical network. To switch off/on the system from/to the electrical network in the system provides a switching element (SE). Transmission of energy from generating sources to the consumer is carried out through distribution equipment (DE). For the accumulation of electric energy in the system, it is proposed to use two groups of electrochemical storage accumulators. In this case, each accumulator unit is connected alternately to the voltage rectifier of the electrical network or to a photovoltaic converter panel for charging them and to the voltage inverter – for power supply to consumers in such a way that one accumulator unit always has a maximum charge (≈100%) and was ready for the backup power of consumers. In a separate block, a group of consumers is allocated (circulating pumps, heat storage backup heat sources), which constitute the load of their own needs (LON) of the proposed system.

The system also includes an automatically controlled ballast load (BL) designed to dispose of the potential excess power generated by the PCP. As BL uses, in addition to the accumulator unit, the system of additional heating of the heat exchange surface of the heat accumulator (HA) of the improved design. The connection of the latter allows both the intensification of the accumulation process and the accumulation of surplus generated electricity in it, thereby turning it into heat. But, under conditions of high cloudy, in the transition and heating periods there is no excess energy, then the system's operation goes into its consumption, not generation. In this case, the heat energy deficit is covered by the inclusion of the solid-fuel boiler (SFB) system, and the electric - from electrical network. Another one source of heat energy in TEGU can be solar collector system (SCS) which connected with HA by buffer vessel (BV).

With a view to improving efficiency of the thermal energy generation unit, an analysis of existing structures of heat storage devices [18–22] was carried out. Owing to conducted analysis by using the package COMSOL Multiphysics 3.5a., a new axonometric model of the accumulator (see Fig. 2a) proposed for the storage of heat based on the phase transition of heat-accumulating material [23, 24]. Moreover, numerical simulation and investigation of processes of hydrodynamics and heat transfer in the experimental module of the developed heat accumulator (see Fig. 2b) during phase transformations of accumulating material have been carried out. As a result, the basic regularities of the investigated processes are found and recommendations on the choice of the geometry of the location of heat sources inside volume of the heat accumulator are given in source [24].

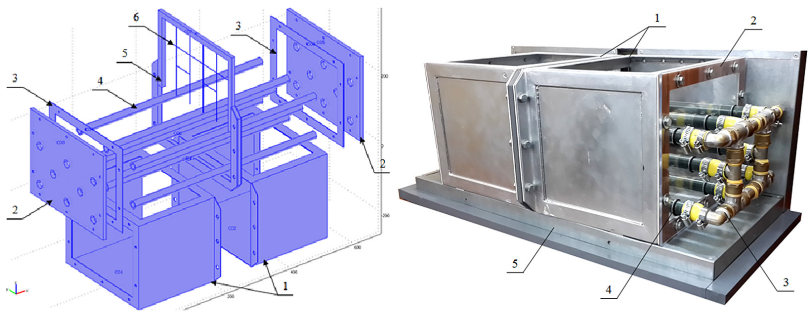


Fig. 2. Axonometric view of the model of heat accumulator (a): 1 – frame; 2 – end cap; 3 – sealing; 4 – tube bundle; 5 – movable frame; 6 – sensors grid, and general view of the experimental module (b): 1 – collapsible case; 2 – end cap; 3 – distribution collector; 4 – tube bundle; 5 – thermal insulation panel

In the proposed design of the developed heat accumulator, the coolant moves in the system of heating tubes which can emit or absorb the heat energy that is accumulated or taken from the accumulating material. As the heat-accumulating material chose Paraffin T3 with a phase transition temperature T_f = 54–56 °C which is wide spread applied PCM with nontoxic and noncorrosive properties. Nevertheless, utilization of it limited to its low conductivity. One of the perspective method to enhance the thermal conductivity of paraffin based PCM is uses of high conductivity nanoparticles.

Researches of the influence of micro- and nanoparticles of metals on the intensity of processes of phase changes of pure and composite paraffin was carried out on a developed experimental installation (see Fig. 3). It consists of two identical experimental modules, one of which is to be imbued with pure paraffin T3, and the second one is to be filled with the same material and nanoparticles with a high coefficient of thermal conductivity. As the example of that material, micro- and nanoparticles of copper are proposed to be used. It must be italicized that the plant is additionally equipped with a cylindrical heat energy source having a power of 1.5 kW, a laboratory autotransformer, a gauging set and equipment for temperature measuring purposes using thermo-couples placed on the surface of the heat energy source and in the volume of paraffine.

a b c

Fig. 3. General view of the experimental installation: (a) experimental modules with pure paraffin T3, (b) experimental modules with composition of paraffin T3 and nanoparticles with a high coefficient of thermal conductivity, (c) arrangement of thermocouples on a "temperature grid" installed into experimental module

For the measuring temperature procedures, carried out on the surface of a cylindrical heat source, the K-type thermocouples are used. Furthermore, in the control process of temperature fields directly in the PCM volume, 5-way thermocouples are involved creating the so-called "temperature grid" (Fig. 3c). This "grid" was executed in the form of a frame with fixed thermocouples on it and placed inside the modules. This allowed us to trace the dynamics of temperature fields in the volume of PCM of the experimental modules.

To determine the influence of temperature and impurities on the structural transformations of PCM experimentally, a spectroscopy technique (Raman spectroscopy) is utilised, which is a non-destructive method for the reflection of crystallization processes for the analysis of thermodynamic properties. The thought is particularly being given to using pure paraffin as an initial material.

Computer numerical simulation was performed for pure paraffin T3 and paraffin with metal nanoparticles. The mathematical model of heat and mass transfer processes in the phase transformations of the accumulation material includes the Navier-Stokes equation and the convective heat transfer equation with the use of the package of applications COMSOL Multiphysics 3.5a.

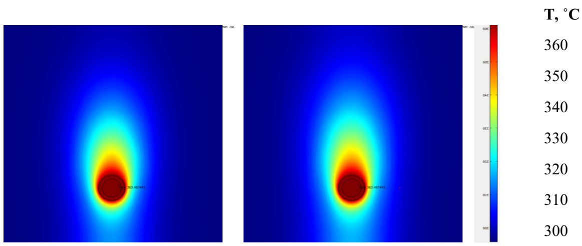
3 Results and Discussion

Experimental studies have shown that the distribution of metallic micro- and nanoparticles in the volume of the main substance depends on the size of the particles. In composite materials having fractions of nanoparticles of 0.2 mm or larger, the particles were noticed to be settled on the bottom of the chamber after paraffin melting.

As a result, this issue initiated their alleviation effect on the processes of heat accumulation in accumulators. Therefore, in this work, experimental studies were carried out on metallic nanoparticles that did not have a sedimentation effect.

For studying the melting processes and the dynamics of temperature distribution in PCM, experimentally based studies (Fig. 2 and 3) were successfully performed. They were carried out with more precision and certainty laboratory conditions for pure paraffin and paraffin with copper filler with a fraction size of 0.07–0.1 mm (volume ratio 20:1). As a result of the performed experimental studies of transfer processes during phase transformations of pure and composite paraffin, dependences of temperature indices of HAM on time were obtained. The data analysis process of the obtained dependences indicates an increase in temperature throughout the volume in the presence of copper fraction compared with pure paraffin, which averaged 4–6%. This fact indicates an increase in the thermal conductivity of composite paraffin with copper nanoparticles.

Result of numerical simulation, the temperature distributions in the volume of accumulative material for pure paraffin and paraffin with copper filler can be visually presented in Fig. 4. As shown by the analysis of the obtained distributions, the averaged temperature indices in the composite PCM as being 6–9% higher than those in pure paraffin, which correlates with the data obtained in experimental studies.



a b

Fig. 4. Temperature distributions in volume of PCM: a - pure paraffin; b - paraffin with copper nanoparticles

In addition to numerical and experimental investigation of the processes of heat accumulation mentioned earlier, proposed heat accumulator application analysis for the system of integrated energy supply of consumers from the energy of traditional and alternative sources with the use of electric and heat accumulators. The number of photovoltaic converters (at a base power of one module of 100 W) is calculated, which is necessary to cover the load of consumers from 500 to 10000 W depending on the period of the year. Average duration of work lasting during the day 8–12 h. The results of calculations are presented in Fig. 5.

The probable duration of uninterrupted power supply of consumers is determined. For example, from two 12-V groups of accumulators, at an active power of consumers from 500 to 2000 W and the temperature of the electrolyte accumulator: +20… −20 °C. The nominal capacity of one accumulator belonging to each group is 100 A·h. The time of continuous supply of consumers (Fig. 6a), capacity consumption and the “discharge” of the heat accumulator (Fig. 6b) are determined. These values are calculated depending on the load capacity and the number of m heat accumulators in the group from 2 to 4 pcs. In addition, the magnitude of the power “discharge” is determined depending on the temperature of the electrolyte and the degree of “charge” of the heat accumulator.

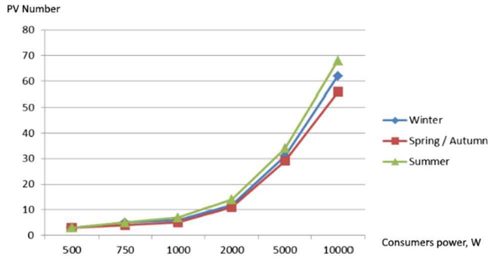


Fig. 5. The ratio of the number of PV depending on the power of consumers of el. Energy

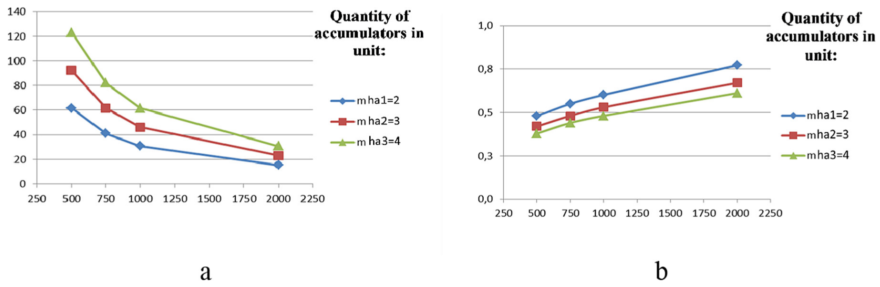


Fig. 6. The ratio of the duration of the discharge (a) and the coefficient of “discharge” (b) of the accumulator unit depending on the power of consumers

It has been established that in order to ensure efficient operation of autonomous power supply of consumers with a nominal electric power of 2000 W for 24 h and a peak (up to 2 h) with a power of 5000 W, the system should consist of a photovoltaic panel with an active area of heliopoles of 7,7–8,9 m^2 and 12 V accumulator of electric power with a nominal capacity of 315–365 A·h, and with a thermal power of 700 W load - from a solar collector area of 4.5–5.8 m^2 and one accumulator of heat of phase transition with a power of 8 kW.

4 Conclusion

1. The main variants of construction of existing systems of combined power supply of consumers, among other things, from alternative sources of energy are analyzed. The low efficiency of using their power and the high cost of the unit of energy received is revealed. As a result, the system of complex energy supply of consumers with the use of alternative sources and combined energy accumulators was proposed. It is effective for use in various climatic zones.
2. Experimental and numerical investigations have proved the feasibility of using metallic micro and nanoparticles of high thermal conductivity to intensify the process of phase changes in pure paraffin and increase the efficiency of heat accumulators.
3. For the proposed system of integrated energy supply of consumers, initial data on the choice of effective parameters of its component composition is obtained, depending on the climatic conditions of the accommodation and capacity of the domestic consumer. It has been established that in order to ensure efficient operation of autonomous power supply of consumers with a nominal electric power of 2000 W for 24 h and a peak (up to 2 h) with a power of 5000 W, the system should consist of a photovoltaic panel with an active area of heliopoles of 7,7–8,9 m^2 and 12 V accumulator of electric power with a nominal capacity of 315–365 A·h, and with a thermal power of 700 W load from a solar collector area of 4.5–5.8 m^2 and one accumulator of heat of phase transition with a power of 8 kW.

References

1. Badescu, V.: Modeling Solar Radiation at the Earth's Surface. Springer, Heidelberg (2008)
2. Todorovic, M.S., et al.: 3.5 MW seawater heat pump assisted multipurpose solar system's 25 years of operation. ASHRAE Trans. **116**(1), 227+ (2010). Accessed 21 May 2020
3. Abbott, R.M.: Solar power system using thermal storage and cascaded thermal electric converters. U.S. Patent No. 6,313,391 (2001)
4. Trp, A.: An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit. Solar Energy, **79**(6), 648–660 (2005)
5. Suganya, G., Bapu, B.R.R.: Experimental studies on performance of latent heat thermal energy storage unit integrated with solar water heater. Int. J. Chem. Sci. **14**(2), 1165–1171 (2016)
6. Zhang, Q., Huo, Y., Rao, Z.: Numerical study on solid–liquid phase change in paraffin as phase change material for battery thermal management. Sci. Bull. **61**(5), 391–400 (2016)
7. Nasieka, I., et al.: An analysis of the specificity of defects embedded into (1 0 0) and (1 1 1) faceted CVD diamond microcrystals grown on Si and Mo substrates by using E/H field discharge. J. Cryst. Growth **491**, 103–110 (2018)
8. da Cunha, J.P., Eames, P.: Thermal energy storage for low and medium temperature applications using phase change materials – a review. Appl. Energy **177**, 227–238 (2016)
9. Liu, L., Su, D., Tang, Y., Fang, G.: Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renew. Sustain. Energy Rev. **62**, 305–317 (2016)

10. Fan, L., Khodadadi, J.M.: Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renew. Sustain. Energy Rev. **15**(1), 24–46 (2011)
11. Agyenim, F., Hewitt, N., Eames, P., Smyth, M.: A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renew. Sustain. Energy Rev. **14**(2), 615–628 (2010)
12. Jegadheeswaran, S., Sanjay, D.: Pohekar: performance enhancement in latent heat thermal storage system: a review. Renew. Sustain. Energy Rev. **13**(9), 2225–2244 (2009)
13. Kuboth, S., König-Haagen, A., Brüggemann, D.: Numerical analysis of shell-and-tube type latent thermal energy storage performance with different arrangements of circular fins. Energies, **10**(3), 274 (2017)
14. Huo, Y., Rao, Z.: Lattice boltzmann simulation for solid-liquid phase change phenomenon of phase change material under constant heat flux. Int. J. Heat Mass Transf. **86**, 197–206 (2015)
15. Nabeel, S.D., et. al.: Experimental and numerical investigation of melting of phase change material/nanoparticle suspensions in a square container subjected to a constant heat flux. Int. J. Heat Mass Transfer, **66**, 672–683 (2013)
16. Kaviarasu, C., Prakash, D.: Review on change material with nanoparticle in engineering application. J. Eng. Sci. Technol. Rev. **9**(4), 26–36 (2016)
17. Said, M.A., Hamdy, H.: Effect of using nanoparticles on the performance of thermal energy storage of phase change material coupled with air-conditioning unit. Energy Convers. Manag. **171**(1), 903–916 (2018)
18. Sharma, A., Tyagi, V.V., Chen C.R., Buddhi, D.: Review on thermal energy storage with phase change materials and applications. Renew. Sustain. Energy Rev. **13**(2), 318–345 (2009)
19. Gorobets, V., Treputnev, V.: Heat transfer and the motion of the interphase boundary, when a heat-accumulating material is melted near a horizontal heat source with section finning. Teplofiz. Vys. Temp. **33**(4), 588–593 (1995)
20. Chen, S.L., Hsiao, M.J.: Heat pipe circuit type thermal battery. U.S. Patent No. 6,220,337 (2001)
21. Naumov, A.L., Serov, S.F., Efremov, V.V., Degtyarev, N.S.: Heat accumulator. RU Patent No. 2,436,020 (2011)
22. Thermal Batteries: All about storing solar heat (2019). Accessed 28 Feb
23. Antypov, I.: Numerical study of heat transfer processes in low-temperature heat accumulator in phase transformations accumulate material. Scientific Herald of the National University of Life and Environmental Sciences of Ukraine, vol. 224, pp. 208–213 (2015)
24. Gorobets, V., Antypov, I., Trokhaniak, V., Bohdan, Y.: Experimental and numerical studies of heat and mass transfer in low-temperature heat accumulator with phase transformations of accumulating material. In: MATEC Web of Conferences, vol. 240 (2018)