Development of heat storage unit based on the phase change materials for mining machinery with combustion engines

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The paper deals with the possibility of accumulation of useful heat of mining machinery with combustion engines by a heat storage unit that uses phase change of accumulated material. The concept of heat storage unit proposed by authors uses a unique combination of phase change material - sodium acetate trihydrate and cellular structure of metal foam, which reduces the fundamental lack of commonly used PCM - low thermal conductivity. The heterogeneous structure of the metal foam and sodium acetate trihydrate creates suitable conditions for increasing the thermal conductivity in the whole volume of the heat storage unit. The presented analysis focuses on the part of the verification of the functionality of the proposed heat storage unit, which is in this case characterised by the first phase of working cycle in which heat storage unit receives heat from selected source. The experiment that assesses the heat accumulation of heat storage unit was conducted on a functional prototype in Centre of Renewable Energy Sources Faculty BERG on an experimental apparatus designed and manufactured by the authors. Results of realized experiments are represented by the temperature curve of the phase change material (sodium acetate trihydrate), which shape and trend show that the authors manage to create a structure of heat storage unit and ensure such conditions under which a process of heat accumulation takes place in the whole volume of the heat storage unit.

Key words: *Phase Changing Materials, Heat Accumulation, Mining Machinery*

Introduction

Useful heat resulting from the operation of mining machinery with a combustion engine (stationary or mobile) is an unused energy potential in the form of exhaust gas, coolants or air, which are heat sources with varying energy levels. This potential can be suitably converted to further uses and bring immediate savings in fuel consumption by improving the operating parameters of the machines, respectively extending the lifecycle in terms of reducing wear of individual parts, and thus extended service intervals (Elevli, et al., 2010), (Mohammadi et al., 2016). Since mining industry is energy intensive sector, many approaches that can reduce energy demands are studied, including use of renewable energy sources or energy storage (Křivík, et al., 2006), (Zimáková, et al., 2015), (Dostál, et al., 2012), (Rybár, et al., 2015). A small range of industrial applications and technology is dealing with useful heat, i.e. heat recuperation with direct use, thermoelectric generators (Kim, et al., 2016) or heat storages with delayed use (Shon, et al., 2014).

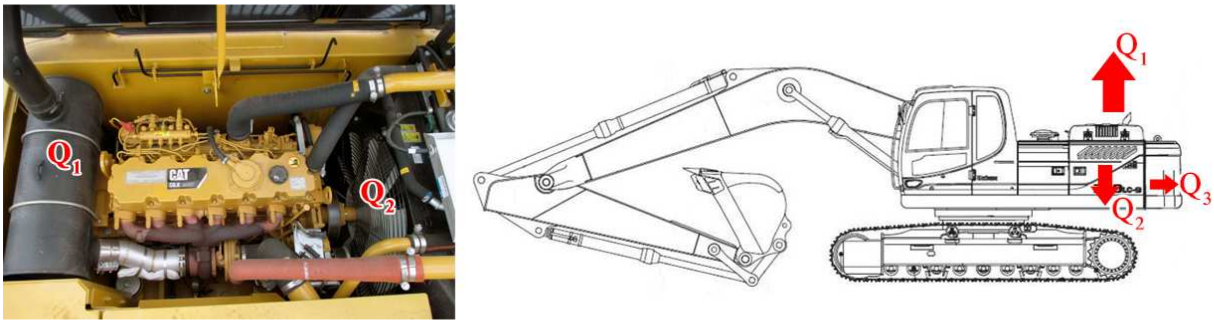

Fig. 1. Example of the most important sources of useful heat from excavator, as typical mining machines, Q_1 - heat from exhaust gas, Q_2 - coolants, Q_3 - hydraulic circuit

Identifying sources of useful heat of mining machines is mainly focused into the engine compartment, where heat exchangers of operation fluid and gases, the outlet of exhaust gas and drivetrain of the hydraulic circuit are located (see Fig. 1). In terms of energy flow, the exhaust gas outlet from combustion engine that provides constant heat flux with sufficient thermal capacity is dominant. To a lesser degree, it is possible to use heat fluxes from the cooling space of operation fluids and gases, respectively from a hydraulic pump in the hydraulic circuit. The last mentioned sources represent sources with low energy potential which should be advantageous for designs with different concepts of heat accumulators. The heat energy contained in the exhaust

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gas and cooling systems generally represents 60-70 % of the total energy content of the fuel (Spellman, 2013). Heat accumulation and storage unit with appropriate design and thermal capacity located in the corresponding position of the mining machine can improve the economy of operation and the life of the construction parts, particularly in difficult climatic conditions. A good example is the possibility of elimination of cold engine starts where the heat storage unit allows heating of the engine before the start of operation with heat stored from the previous operation. The inclusion of the heat storage unit allows obtaining a balanced operation of the engine (or machine) in terms of reduction of thermal shocks and stress of working fluids, which represents the negative side of the operation. However, such constructed heat storage unit is bounded to the assumption that it will be able to overcome longer periods with stored heat without progressive reduction of the amount of accumulated heat. This allows some materials to use phase change, which may also be in the state of super cooling. The concept of heat storage unit proposed by the authors that works with phase change materials (hereinafter PCM) in combination with metal foams is a suitable technical solution that can be applied to the above-mentioned operating conditions of machines, which are not limited to the mining machines, but span a wide range of machinery producing significant amounts of energy in the form of useful heat. The incorporation of the proposed heat storage units into the mining machines is also suitable due to their significant operation weight, thus the ratio of the weight of heat storage unit to the total weight of the machine is negligible.

From a physical point of view, accumulation of heat is possible in several ways: accumulation of sensible heat, latent heat, sorption heat and chemical heat (Bajnóczy, et al., 1999). In recent years, the use of heat accumulation operating on the principle of phase change of PCM where latent heat is stored is getting attention. As reported by Mehling, et al. (2008), latent heat is one of the most efficient ways to store thermal energy. Materials suitable for heat storage should achieve the greatest values of accumulation of heat energy in a minimum volume of material. Additional requirements for PCM include: cyclic stability, flame resistance, low volume changes associated with phase changes, non-corrosive properties and low tendency to super cooling.

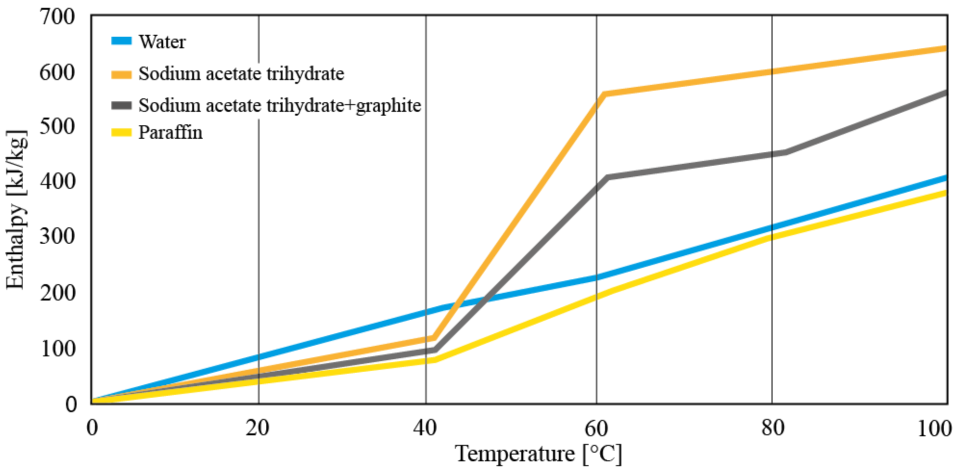

Fig. 2. Comparison of heat storage capacity of selected materials (Huang, et al., 2010).

In terms of the ratio between the storage capacity of the materials and their weights, organic (waxes) and inorganic (hydrated salts) PCM are almost comparable. In a comparison of the amount of accumulated heat to the volume of accumulated material, there is a clear significant difference in density between the accumulation of organic (waxes) and inorganic (hydrated salt) PCM.

The operating cycle of such conceived heat storage units can be divided into three phases. The first phase involves the accumulation (charging) of the heat storage unit. In the second phase, there is a stabilisation of heat storage unit, and in the third phase, there is the release of stored energy. The temperature of accumulation material (PCM) is increasing in the charging phase. In the first part of this phase, a sensible heat without phase change of PCM is accumulated. For sodium acetate trihydrate, this part is limited to a temperature of 58°C. Above this temperature, latent heat is accumulated; this accumulation is ended at the moment when the phase change from solid to liquid phase is completed in the whole volume of heat storage unit, i.e. when PCM receive all latent heat in relation to its volume (e.g. for the sodium acetate trihydrate it is 265 $kJ.kg^{-1}$). If the heat storage unit received more energy, the temperature of PCM is increasing and only sensible heat is accumulated. The first phase is followed by super cooling phase, which stabilises heat storage unit by preventing unwanted nucleation and thus the premature release of the stored energy (Huang, et al., 2010). When PCM is in super cooling phase, heat storage unit is in the state of liquid phase below to the point of phase change (58 °C for sodium acetate trihydrate). The course of the temperature for the phases of accumulation and the super cooling are shown in Figure 3.

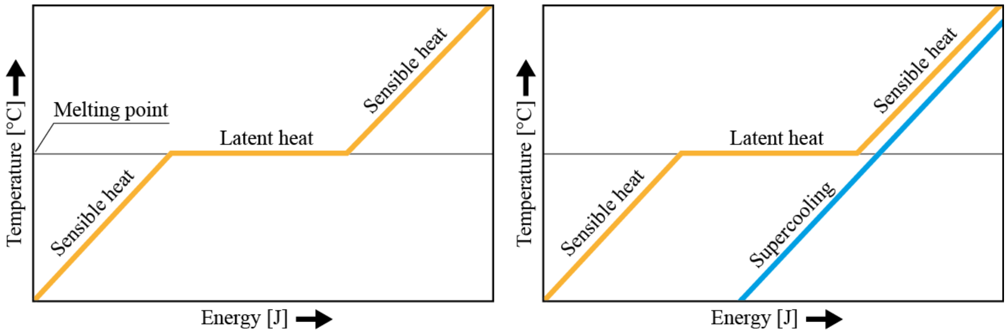

Fig. 3. Temperature curves of PCM for the accumulation phase (left) and super cooling phase (right), (Huang, et al., 2010).

An important characteristic of PCM materials in terms of thermal properties is their low thermal conductivity (Srikanth et al., 2017). This feature presents some conceptual limitation of creating heat storage unit based on PCM, which is reflected in the length of time for melting and solidifying of PCM. Problems related to the heat distribution in PCM are presented, for example by Himanshu (2011), wherein author experimentally tested possibility of improving heat transfer in PCM (paraffin wax) with the use of the open cell structure of the copper foams. By adding metal foams in paraffin, the thermal conductivity of the created structure increased from 16 to 18 times compared to pure paraffin. Another way of increasing the thermal conductivity of PCM is the application of additive, which produces a heterogeneous mixture with PCM (Choi, et al., 2014), (Ansone, et al., 2016), (Kumaresan, et al., 2013).

A specific concept of the storage unit, which is presented in this paper, is a combination of PCM material - sodium acetate trihydrate and a spatial structure consisting of blocks of metal foam with an open pore structure that in this heterogeneous spatial arrangement creates heat exchanger. This unique combination is designed with the intent to eliminate characteristically low thermal conductivity of PCM materials.

Methodology

The manufactured and assembled prototype of heat storage unit has a cylindrical shape with the base in the form of an annulus. The used metal foam has an outer diameter of the cylinder of 50 mm and inner of 12 mm. Height of the metal foam cylinder, and thus the whole heat storage unit, is 103 mm. The metal foam is characterised by an open structure of pores with a pore density of 10 PPI (pores per inch), and total porosity of 96%. The basic material of metal foam is copper. The second component of the heat storage unit, thus PCM, is sodium acetate trihydrate ($C_2H_3NaO_2.3H_2O$) with melting temperature of 58°C and latent heat capacity 265 kJ.kg^{-1}. The volume of used PCM that fills pores of metal foam was 184.3 cm^3, respectively, by using volumetric mass density 1.45 g.cm^{-3}. The total mass of used PCM was 267.235 g. In order to improve operational and technical characteristics of presented prototype, sodium acetate trihydrate in the composition of 59.86% sodium acetate anhydrous and 40.14% water was used. The heat storage unit consists of a copper pipe to which a copper metal foam annulus was soldered. This object was enclosed with acrylic panels, respectively acrylic tube with an air layer left above the metal foam, which compensates volume changes of PCM caused by phase changing and temperature increase. A manufactured prototype of heat storage unit is shown in Figure 4.

Fig. 4. Prototype of heat storage unit based on PCM.

Tab. 1 Key parameters of experimental heat storage unit

Parameter	Values	Unit
Shape of heat-accumulation unit	Annulus cylinder	/
Dimensions of heat-accumulation unit	Φ50(12)x103	mm
Type of PCM	Sodium acetate trihydrate	/
Composition of PCM	59.86 % sodium acetate anhydrous 40.14 % water	/
Volume of PCM filling	184,3	cm^3
Latent heat of PCM	265	$kJ.kg^{-1}$
Temperature of phase change	58	°C

The total possible amount of accumulated energy of heat storage unit is determined by calculation according to Eq. 1 to Eq. 3:

$$Q_A = Q_{solid} + m \cdot Q_L + Q_{liquid} \quad (1)$$

$$Q_{solid} = m \cdot c_{solid} \cdot \Delta t_{solid} \quad (2)$$

$$Q_{liquid} = m \cdot c_{liquid} \cdot \Delta t_{liquid} \quad (3)$$

where, Q_A - the total amount of accumulated energy, Q_{solid} - the sensible heat of solid phase, Q_L - latent heat of PCM, Q_{liquid} - the sensible heat of liquid phase, m - the weight of PCM. In Eq. 1 and Eq. 2 is c_{solid}, respectively c_{liquid} specific heat capacity of solid, respectively liquid phase and Δt_{solid}, respectively Δt_{liquid} is the difference between temperatures of solid, respectively liquid phase, given the temperature of phase change of sodium acetate trihydrate.

The principle of the physical experiment was based on the flow of heat transfer medium (water) with a temperature of 80 °C through an inner copper pipe of the heat storage unit, what simulates source of useful heat from the combustion engine. Heat flux from heat transfer medium flows through the structure of metal foam where heat was transferred to sodium acetate trihydrate, changing its temperature and phase with a simultaneous accumulation of sensible and latent heat. The task of thus conceived experiment was to test the capability of heat transfer from the heat source through the structure of metal foam to the PCM - sodium acetate trihydrate.

The presented experiment was performed at the Centre of Renewable Energy Sources of the Faculty BERG on the experimental apparatus designed and manufactured by the authors. The heat storage unit described in the previous section was installed in this apparatus. The design of experimental apparatus was based on analysis of the input conditions in order to induce and control non-stationary processes from the view of changing temperatures and phase changing of PCM. The experimental apparatus allowed to supply a constant heat flux from heat transfer medium which circulated in hydraulic circuit, depicted in Figure 5, where: 1 - heat storage unit, 2 - flowmeter, 3 - flow control, 4 - flow heater, 5 - expansion vessel, 6 - hydraulic pump, TC1 to TC4 - thermocouples probes.

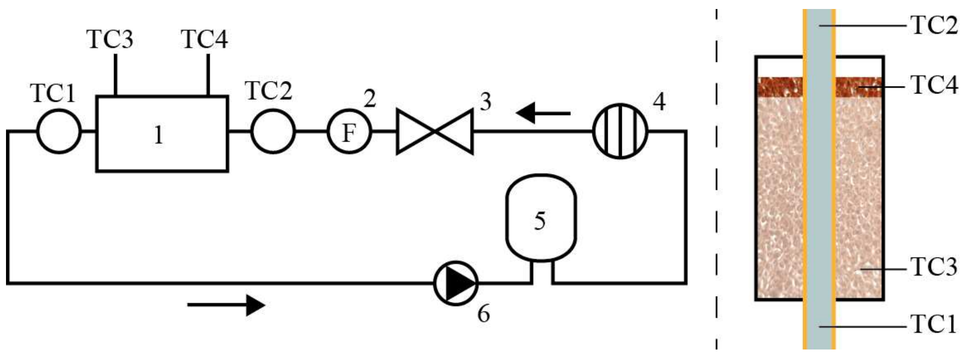

Fig. 5. Schematic diagram of hydraulic circuit (left) and heat storage unit with depicted position of thermocouple probes (right).

In terms of verifying the functionality of the combination of the metal foam structure and sodium acetate trihydrate as a thermal storage unit, it was necessary to measure the temperature of the PCM, i.e. sodium acetate trihydrate as well as the temperature of the metal foam using thermocouple probes that are labelled as TC3 and TC4. Thermocouple probes labelled as TC1 and TC2 measured the temperature of heat transfer medium before and after heat storage unit, as it is depicted in Figure 5. The experimental apparatus was supplemented with measuring devices, which consist from thermocouple probes KIMO TTKE-363 (type K, range from -40 °C to +400 °C), data acquisition system KIMO AMI 300 with temperature range from -100 °C to +250 °C with total uncertainty ± 0.4 %. The step of data recording was 10 s. Flow rate of heat transfer medium was monitored with analogous rotameter with the range of 0.3 to 1.5 l/min and uncertainty ±10 % F.S.

Status of phase changing of sodium acetate trihydrate was also monitored and recorded in the form of a time-lapse video by using a camera located near the heat storage unit. The frequency of image capture was determined with respect to the rate of phase change to an interval of 5 minutes. The camera lens was equipped with a polarization filter, which eliminates the glare from an outer acrylic tube of heat storage unit. On the body of heat storage unit, a measuring tape, allowing accurate tracking of phase change of sodium acetate trihydrate, was placed.

Results and Discussion

The presented analysis of proposed heat storage unit focuses on the part of the verification of its functionality, which is in this case characterised by the first phase of working cycle, where heat storage unit receives and accumulates heat energy from selected source. This process involves phase change of PCM, which has at the beginning solids phase and with raising temperature is changing to the liquid phase. The melting point of sodium acetate trihydrate, which was used in the presented work, is 58 °C.

In the first phase of working cycle, sensible and latent heat are accumulated. For the proposed heat storage unit, their amount was calculated using Eq. 1 to Eq. 3. The results of the calculation that reflect the real dimensions and characteristics of sodium acetate trihydrate for the amount of accumulated sensible heat is Q_{solid} equal 28,64 kJ. This heat is delivered within temperature difference Δt = 58 – 20 °C, since the ambient temperature at the start of the experiment was 20°C and sensible heat is accumulated to the temperature of 58 °C. The amount of accumulated latent heat $m.Q_L$ with the used weight of sodium acetate trihydrate is equal to 70.8 kJ. Because the sodium acetate trihydrate in the composition of 59.86% sodium acetate anhydrous and 40.14% water was used in the heat storage unit, it was necessary, according to Nohejl (2016), to raise the temperature of PCM to 65°C to ensure phase change from solid to liquid in the whole volume of heat storage unit. The amount of sensible heat accumulated in this process that occurs in temperature difference Δt = 65 - 58°C is $Q_{liquidus}$ = 5.7 kJ. Thus, the resulting delivered heat represents a value of 105.1 kJ from which the useful heat that is stored for later use is 70.8 kJ (described for a proposed heat storage unit).

Figure 7 shows the temperature curve of the heat transfer medium simulating the useful heat of the combustion engine (TC1) and the temperature of PCM - sodium acetate trihydrate (TC3). Due to the used construction of the heat storage unit in terms of heat transfer from the inner copper tube through the structure of the metal foam to the PCM, the temperature of the heat transfer fluid was selected to 80°C. The temperature was experimentally determined at the trial operation of experimental apparatus and provides sufficient heat flux and therefore the temperature increase of the PCM. The visible anomaly of thermocouple probes TC1 in the initial part of the curve represents the error in controlling of flow heater, but as can be seen, it was quickly fixed.

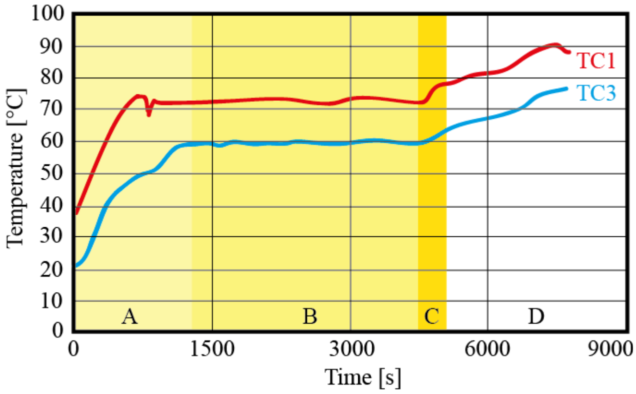

Fig. 7. Temperature curves of PCM and heat transfer medium at the inlet to heat storage unit.

From the shape of temperature curve for TC3 thermocouple probe, which measured the temperature of sodium acetate trihydrate, phases of accumulation can be clearly recognised. The first part, when sensible heat is delivered (labelled as A), is characterised by a steep rise in temperature to the point at 58°C. The second part is the accumulation of latent heat (labelled as B), which takes place at a standard temperature of 58°C, a horizontal course without major fluctuations proves the success of the concept in terms of its function which is storing the latent heat of used PCM. After this part, which in the shown experiment ended at time t=+4500s, the temperature of the heat storage unit increased to 65 °C ensuring complete phase change from solid to liquid state (labelled as C). The last part shown in Figure 7 represents the experimental introduction of the extreme operating conditions in order to detect design and construction errors of the heat storage prototype based on PCM.

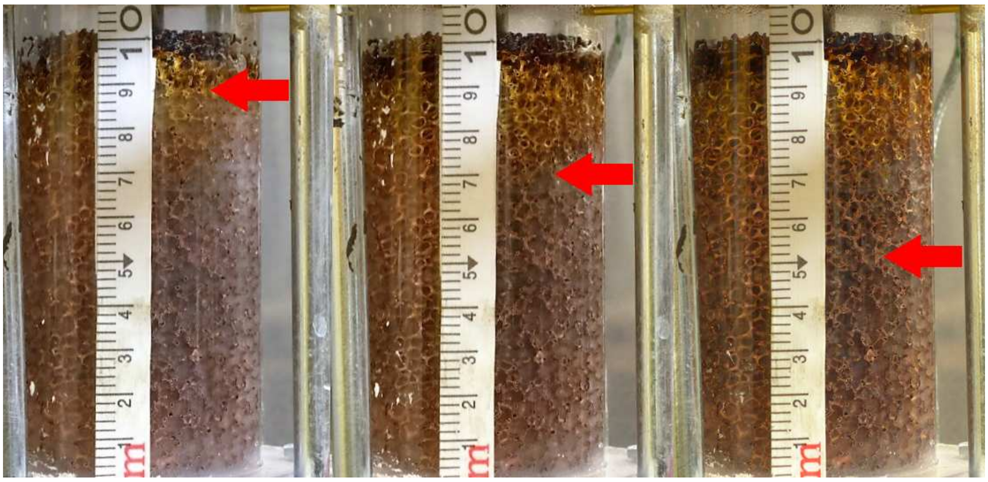

Fig. 8. Time-lapse image of phase change in heat storage unit (red arrow points to level between solid and liquid phase).

In addition to the recording of the temperature from thermocouple probes TC1, TC2, TC3 and TC4, the process of heat accumulation of the proposed heat storage unit was monitored by capturing the image at regular intervals without changing the unit position to the axis of the lens. By time-lapse recording obtained by this way, it is possible to observe the gradual phase change of PCM in the direction of the vertical axis of the heat storage unit. The process of phase change started at the point with the highest temperature, in this case at the point of entry of heat transfer medium into the inner copper pipe. Figure 8 shows the phase change process in the second part of accumulation when sensible heat is already accumulated, and the heat storage unit begins to accumulate latent heat and thus changing its phase from solid to liquid. The rate of phase change of sodium acetate trihydrate was 3 $cm.h^{-1}$ in the vertical axis. However, it is necessary to emphasise that the inner configuration of described heat storage unit was not designed for quick heat accumulation (i.e. fast phase change of PCM), but for testing the functionality of the connection of PCM and metal foam structure.

Next steps in the development process leading to the final product are directed to the experiments related to the super cooling phase of the working cycle. In terms of design, it is necessary to ensure the inner configuration of heat storage unit in a way that there will not occur uncontrolled nucleation of PCM and thus release the accumulated heat. The final step of the proposal, which is dependent on the successful super cooling and stabilisation of PCM, is ensuring fully controllable nucleation (when heat is released) in an appropriate way and at any time period.

Conclusion

Accumulation of useful heat of mining machines or combustion engines and its re-use is a relatively new concept that allows eliminating some of the negative operating conditions related primarily to unfavourable climatic conditions (cold engine start, temperature variations of operation mediums, elimination of thermal shocks, etc.). The presented concept of heat accumulation by the use of heat storage units based on PCM allows this energy store and uses it with time delays when it is needed. The uniqueness of the proposed concept lies in the simultaneous use of metal foam structure and PCM - sodium acetate trihydrate, which ensures sufficient thermal conductivity, which has a low value when the sodium acetate trihydrate is used alone and was limiting factor for the further expansion of PCM storage. The functionality of this concept was verified by physical experiment that simulates the accumulation phase of heat storage unit with the use of a heat source in the form of flowing heat transfer medium giving an analogy to conventional mining machines or combustion engines. The experiment was carried out in the Centre of Renewable Energy Sources Faculty BERG on the experimental apparatus designed and manufactured by the authors. Published results have shown the functionality of the concept in the first phase of accumulation of useful heat, where authors were able to successfully accumulate latent heat to PCM, which demonstrates temperature curve of PCM with flat part of curve at level of 58 °C, which is related to the phase change of PCM, and therefore, accumulation of heat.

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