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Development of heat accumulation unit based on heterogeneous structure of MF/PCM for cogeneration units

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ABSTRACT

The paper deals with the possibility of heat accumulation within cogeneration system with an energy storage unit, which uses a phase change of the accumulation material. The concept of the heat accumulation unit designed by the authors uses a unique combination of the phase change material (PCM) with sub-cooling effect - sodium acetate trihydrate and the metal foam (MF), which reduces the fundamental disadvantage of commonly used phase change material - low thermal conductivity. The heterogeneous metal foam structure and sodium acetate trihydrate create suitable conditions for increasing thermal conductivity throughout the entire volume of the heat accumulation unit. The research was strictly focused on the mapping of processes related to charging. An experiment that evaluates heat accumulation was performed on a prototype in the Center of Renewable Energy Sources on an experimental device designed and manufactured by the authors. The obtained results show that the authors have succeeded in achieving the heat distribution in the volume of the heat accumulation unit at the level that a complete phase change from solid to liquid phase was achieved.

1. Introduction

The requirement to achieve consistency between immediate energy needs and energy supply is, in many cases difficult to achieve, technically demanding, or economically inefficient. This discrepancy is most evident in the field of renewable energy sources [1,2] or in the specific use of traditional energy sources – for example in the case of small-scale cogeneration units.

One possible optimization of this requirement is to use an energy storage system included in the appropriate part of the device [3,4]. Whether it is electric energy accumulators [5], or heat accumulators [6] their research is coming to the fore and new materials or technical approaches to the designs are being used [7–9].

The combination of cogeneration units and heat accumulators was described by Therani et al. in [10] where authors evaluated the domestic heating operation, which resulted in a calculation of the heat storage material volume. Authors also reported increase in cogeneration unit efficiency and especially a reduction of CO_2 emissions. The management and economy of cogeneration units with heat storage system are dealt, for example, in [11–14].

Specific experimental evaluation of selected heat storage system with the combination of small-scale cogeneration unit is described by Nyutten et al. in [15], where authors dealt with heat storage system using phase change materials (hereinafter PCM). As a PCM were used paraffin, a mixture of magnesium-based hydrates [$Mg(NO_3)_2{\cdot}6H_2O$ and $MgCl_2{\cdot}6H_2O$] and calcium hydroxide – thus the PCM without sub-cooling feature. The results of the experiment confirmed the expected increase in thermal capacity, but the most interesting conclusion was drawn by the study of the temperature course where the necessary temperature for the charging phase was reduced when using PCM.

Above mentioned facts show that the introduction of heat storage system into the cogeneration unit is reasonable and also brings economic and ecological benefits [16–18]. The paper presents a particular heat storage system proposal for small-scale cogeneration systems. The essence of the design lies in the use of suitable properties of the metal foam – high thermal conductivity, and suitable properties of PCM – high thermal capacity and small heat loss in case of PCM with sub-cooling effect.

Subcooling is process when a phase change material in liquid state cools down below its melting point without solidifying; leaving it in a metastable state where the latent heat of fusion is not released. In latent heat storage supercooling has traditionally been seen as an undesired effect that had to be avoided as it prevented the heat of fusion from being released when the melting point of the storage material was reached during the discharge process. This can be done by using various nucleation agents such as Aluminium Nitride Nanoparticles or various

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salts. This principle makes long term thermal energy storage possible by letting the melted salt hydrate remain in supercooled state at ambient temperature in the storage period. Once the heat is needed the solidification of the supercooled solution is triggered and the latent heat of fusion is released as it crystalizes [19].

Thus designed heat storage system has zero heat losses to the environment and stored energy is usable for a long period of time. With the right combination of these properties, heat storage system can be designed with compact dimensions and unique operational characteristics. The use of the presented heat storage system is also possible in other areas and with other energy sources.

The proposed heat accumulation unit uses the principle of latent heat storage of the PCM. According to Mehling et al. in [20], latent heat is one of the most effective ways of storing heat. Materials suitable for heat storage should achieve the highest values of thermal capacity in a minimum volume of material. The operating cycle of the heat accumulators can be divided into three phases. The first stage involves the accumulation of heat (charging), in the second stage the accumulation unit is stabilized and in the third stage, stored heat is released.

The temperature of heat storage material (i.e. PCM) increases during the first (charging) phase. In the first part of this phase, the heat is accumulated without the PCM phase change. After a certain temperature has been exceeded (depending on the used PCM) latent heat begins to accumulate, this accumulation ends at the moment when the phase change from the solid to the liquid phase is completed in the entire volume of the heat storage unit, i.e. when the PCM receives all the latent heat in terms of its volume. If additional heat is supplied to the heat storage unit, the PCM temperature increases, and unit accumulates only sensible heat.

The first phase is followed by a sub-cooling phase that stabilizes the heat accumulation unit by preventing undesired nucleation and thus prematurely releasing the accumulated energy [21]. When PCM is in the sub-cooling phase, the heat storage unit is in the state of the liquid phase below the point of phase change. The theoretical temperature curves for the accumulation and sub-cooling phases are shown in Fig. 1.

An important, but negative, characteristic of PCM is its low thermal conductivity. This property represents a certain conceptual limitation in the construction of a PCM heat accumulation unit. Low thermal conductivity is reflected in the melting (charging) and solidifying (discharging) time. The problems with heat distribution in PCM are presented, for example by Himanshu in [22], where author experimentally tested the possibility of improving heat transfer in PCM (paraffin wax) by using a metal foam with open pore structure, however, author used PCM without sub-cooling effect. By adding metal foams to paraffin, the thermal conductivity of the formed structure increased approximately 16-times compared to pure paraffin. The advantage of the metal foam embedded in the PCM volume is improvement of the thermal conductivity of this heterogeneous structure. Metal foam ligaments create ideal structure for unidirectional heat transfer and its further dissipation into the PCM volume. The high specific surface area, i.e., the interface between the metal foam and the PCM provides suitable properties in terms of improving the thermal conductivity of proposed heat accumulation unit. The area dealing with the thermo-technical properties of the metal foams is widely explored and published in a number of scientific papers, for example in [23–25]. Another way to increase the thermal conductivity of PCM is to apply additives to form a heterogeneous mixture with PCM as is suggested in [26–28].

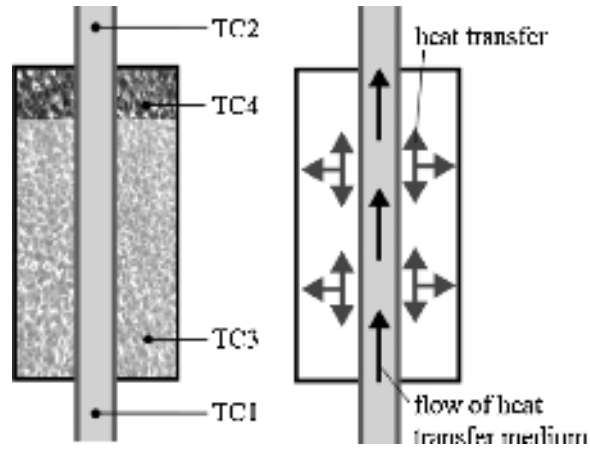

Fig. 2. Concept of heat accumulation unit.

2. Material and methods

The functionality of the heat accumulator concept in first phase of operation cycle was assessed by using a heterogeneous structure consisting of copper metal foam with an open pore structure and PCM - sodium acetate trihydrate [$C_2H_3NaO_2{\cdot}3H_2O$]. This combination was designed to eliminate the characteristic low thermal conductivity of PCM by introducing metal foam that served as a spatial heat exchanger. The basic shape was proposed in the form of a hollow cylinder with inserted heat transfer medium pipe as shown in Fig. 2, which also shows the location of temperature probes as well as the schematic representation of fluid and heat flows.

An essential element of the heat accumulation unit is a block of copper metal foam with an open pore structure shown in Fig. 3. The final shape was made by electrical discharge machining to the form of a hollow cylinder with an outer diameter of 50 mm, an internal diameter of 12 mm and a height of 103 mm. The copper metal foam used in experiment has a pore density of 10 PPI (pores per inch).

The specific characteristics of the copper metal foam required for the design and construction of the prototype were determined by computed tomography using a ZEISS METROTOM 1500 with a

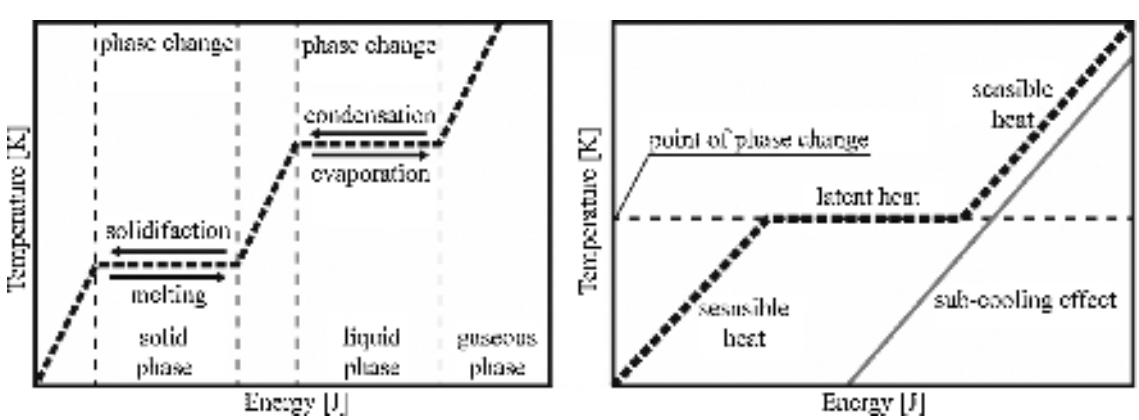

Fig. 1. The temperature curves for the accumulation (left) and sub-cooling (right) phases.

Fig. 3. Block of used copper metal foam.

resolution of 1024 × 1024 pixels and an RTG tube up to 225 kV/225 W with the specified maximum error MPEE = (9 + L / 50) μm where L is the voxel value. Because of the size limitations of the device (height of specimen 110 mm, diameter 170 mm) and need of specimen stand, only part of the metal foam object was scanned.

In all of the following calculations, this fact was taken into account. Before scanning, the calibration and qualification of the subsystems were carried out to verify the functionality of the device. The scanning parameters were chosen based on the requirement of sufficient contrast between the sample and surroundings. The scanning distance (detector distance) and the used power were selected with respect to the voxels and points. The resulting 3D model, which is shown in Fig. 4, was graphically and statistically analyzed in the software VGSTUDIO MAX.

The results of the computed tomography analysis are the

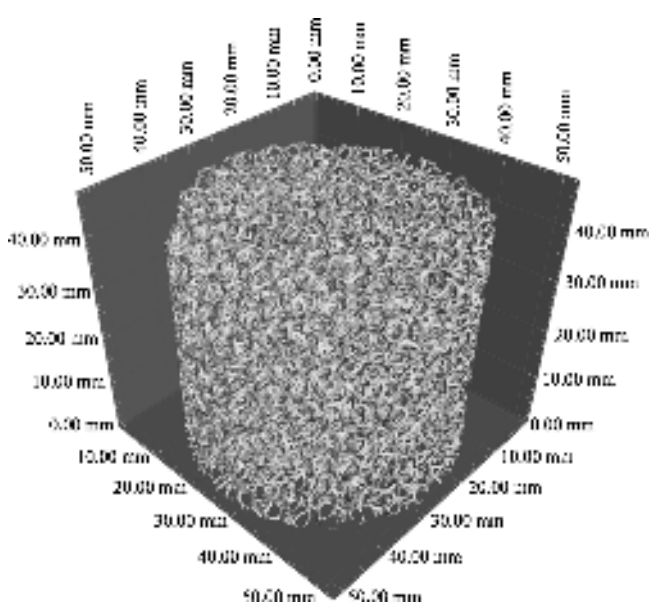

Fig. 4. 3D model of the metal foam sample.

Table 1
Main parameters of the experimental heat accumulation unit.

Parameter	Value	Unit
Shape	Hollow cylinder	/
Material	Copper metal foam	/
Specific heat exchange surface of metal foam	1774	$m^2.m^{-3}$
Metal foam porosity	95	%
Prototype dimensions	Φ50(12) x 103	mm
PCM type	Sodium acetate trihydrate	/
PCM volume	185	cm^3
PCM mass	268	g
Latent heat of PCM	265	$kJ.kg^{-1}$
The temperature of the phase change	58	°C

quantification of a specific surface area - the interface area directly involved in the heat transfer process, with a value of 1 774 $m^2.m^{-3}$ and a total porosity of 95%. On the basis of these results, the volume of the used PCM was determined. As a PCM was used sodium acetate trihydrate with a melting temperature of 58 °C, latent heat capacity 265 $kJ.kg^{-1}$ and volumetric density 1.45 $g.cm^{-3}$. The volume of PCM used in the prototype that fills the metal foam pores was 185 cm^3 and the total weight of the PCM was 268 g. To improve the operational and technical characteristics of the presented prototype was used sodium acetate trihydrate consisting of 60% sodium acetate anhydrous and 40% water. The main parameters of the experimental heat accumulation unit are summarized in Table 1.

3. Experiment

Based on the results of the above analyzes, a final prototype was assembled to verify the function of the heat accumulation process. The prototype consists of a 15 cm copper tube with an outer diameter of 12 mm and a wall thickness of 1 mm to which a metal foam cylinder block has been attached by the brazing joint. The outer envelope consisted of an acrylic tube with an inner diameter of 50 mm, an outside diameter of 60 mm and a length of 110 mm. Approximately 10 mm elongation of the outer acrylic tube in the y-axis was designed to provide a compensation volume during the phase change of used PCM. The top and bottom were closed with acrylic sheets. The final version of the prototype is shown in Fig. 5, where can be seen additional threaded rods ensuring the structural integrity of the entire prototype.

An experiment verifying the functionality of the concept of a proposed heat accumulation unit in first phase i.e. charging phase was carried out at the Centre of Renewable Energy Sources on a measuring apparatus designed and built by the authors. The design of measuring apparatus was based on analysis of input conditions that induce and control non-stationary processes in terms of temperature changes and PCM phase change. Measuring apparatus allowed a constant flow of heat from the heat transfer medium circulating in the hydraulic circuit as shown in Fig. 6.

The experimental operation was based on the gradual introduction of heat into the heat accumulation unit through a heat transfer medium (water) with the temperature of 70 °C, simulating the expected operating conditions of a small-scale cogeneration unit. Heat dissipated through the inner tube casing and brazed joint into the structure of the metal foam and to the volume of the PCM cause increasing of temperature and start of phase change and accumulation of sensible and latent heat in PCM. The main task of this experiment was to test the ability of heat transfer from the heat source through the metal foam structure to PCM.

The temperature characteristics of the experimental operation were recorded with the thermocouple probes whose location is shown in Figs. 2 and 6. The probes marked as TC1 and TC2 were used to record the temperature of the heat transfer medium before and after the heat

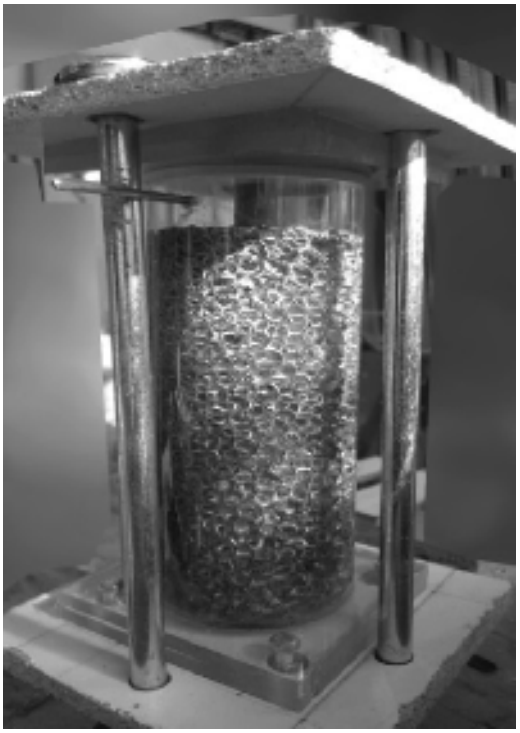

Fig. 5. Prototype of proposed heat accumulation unit.

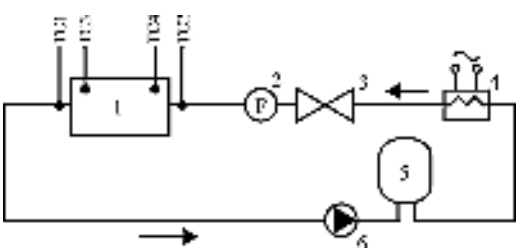

Fig. 6. Schematic diagram of the hydraulic circuit.
(1 – heat accumulation unit, 2 - flowmeter, 3 – flow regulation, 4 – electric flow heater, 5 – expansion vessel, 6 – circulating pump, TC1 to TC4 – thermocouple probes).

accumulation unit, the TC3 and TC4 probes recorded the temperature of the PCM, respectively metal foam. During experiment were used thermocouple probes KIMO TTKE-363 (type K, range from −40 °C to + 400 °C) and 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. The flow rate of heat transfer medium was monitored with analogous rotameter with a range of 0.3 to 1.5 l/min and uncertainty ± 10% F.S.

4. Results and discussion

The results of the experiment include the verification of the functionality of the heat accumulation unit and the detailed mapping of the process during the first phase of the operating cycle, which is characterized by the accumulation of the sensible and latent heat, i.e. the charging phase. The importance of correctly recognizing the behavior of the proposed prototype in the first phase of the operation is crucial due to the need to verify the interaction between metal foam and PCM with the sub-cooling effect.

The first phase of the experimental operation involves a phase change of the PCM from solid to liquid state due to the increasing temperature of PCM. The melting point of the sodium acetate trihydrate is 58 °C. Based on the calorimetric equation was calculated sensible heat

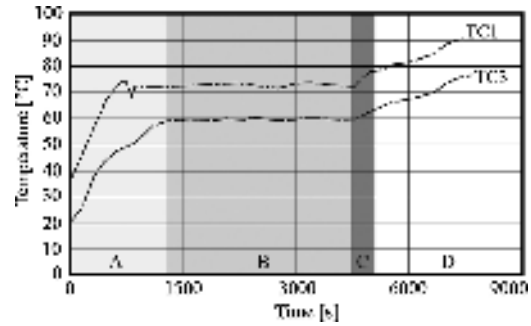

Fig. 7. Temperature curves of heat transfer medium and PCM.

delivered to the heat accumulation unit in the temperature range between 20 °C and 58 °C (20 °C was ambient temperature during the experiment). For the specific thermal capacity of solid sodium acetate trihydrate (2 820 kJ.kg^{-1}. K^{-1}) was calculated delivered and accumulated sensible heat with value Q_{solid} = 28.69 kJ. The amount of accumulated latent heat was as Q_L = 70.8 kJ (for specific latent heat capacity 265 kJ.kg^{-1}).

Since sodium acetate trihydrate consisting of 60% sodium acetate anhydrous and 40% water was used, it is necessary according to [29] increase the PCM temperature to 65 °C to ensure that phase change will take place in the whole volume of PCM. The amount of sensible heat accumulated in this process that occurs at a temperature difference between 58 °C and 65 °C was calculated as $Q_{liquidus}$ = 5.72 kJ (for the specific thermal capacity of liquid sodium acetate trihydrate 3.05 kJ.kg^{-1}. K^{-1}). The resulting delivered heat is therefore 105.36 kJ, of which 70.8 kJ is useful for later use without the thermal loss during storage time, due to the liquid state of PCM, which has ambient temperature.

Fig. 7 shows the temperature curves for the heat transfer medium (TC1) and the temperature of PCM (TC3). The visible anomaly of the TC1 probe at the beginning of the curve represents an error in regulating the flow heater, but as can be seen, the problem has been resolved quickly.

From the shape of the temperature curve for the TC3 thermocouple probe can be clearly identified each stage of the accumulation. The first part, when heat is supplied (marked as A), is characterized by a sharp increase in temperature to 58 °C. The second, horizontal portion of the curve represents latent heat accumulation (marked as B), which runs at a standard temperature of 58 °C, a horizontal course without major fluctuations demonstrates the success of the concept in terms of its function, which is the accumulation of latent heat. After this part, which ended in the experiment at t = 4500 s, the temperature of the heat storage unit was raised to 65 °C to provide a complete phase change from the solid to the liquid state (marked as C). The last part, characterized by an increase in the temperature of the heat transfer media as well as the PCM represents the experimental introduction of extreme operating conditions in order to detect design and construction errors of the prototype.

In addition to the recording of thermocouples TC1, TC2, TC3 and TC4, the process of heat accumulation was monitored by time-lapse recording at regular intervals, without changing the position of the heat accumulation unit to the axis of the lens. In this way, it was possible to record a PCM phase change in the direction of the vertical axis of the heat accumulation unit in accordance with the flow direction of the heat transfer medium. The phase change process started at the highest temperature point, in this case at the heat transfer medium inlet to the inner copper tube.

Fig. 8 shows the process of a phase change in the second part of the operation when the heat is already accumulated and the heat storage unit has started to accumulate latent heat and thus change the state from solid to liquid. The rate of phase change of sodium acetate

Fig. 8. Time-lapse images of the phase change in the heat accumulation unit (arrows show the interface between the solid phase and the liquid phase).

trihydrate was in the vertical axis 3 cm.h^{-1}.

This slow phase change was caused by the internal configuration of the proposed prototype (especially low porosity of used metal foam). However, it has to be underlined that the internal configuration of the described unit was not designed for rapid heat accumulation (i.e., rapid phase change) but to test the functionality of the unique connection of metal foam and PCM with sub-cooling effect in the first phase of operation cycle i.e. charging phase.

The next steps towards the prototype design of the heat accumulation unit for small-scale cogeneration systems are derived from the above-presented results. It is necessary to increase the rate of accumulation as well as to allow the use of heat transfer media at higher temperatures. These disadvantages will eliminate the use of metal foam with higher pore density and segmentation of the desired heat capacity from one volume to multiple heat accumulation units.

For example, if we consider using the concept of the proposed heat accumulation unit in the common suburban civil object with heat demand of 150 000 kJ/day where the need for accumulation would be 50% of this value, the required volume of PCM would be about 283 liters of sodium acetate trihydrate (at a density 1450 kg.m^{-3}). Considering the achieved rate of phase change, the best variant is the use of multiple heat storage units connected to the parallel operation to ensure uniform charging as well as discharge.

The scheme in Fig. 9 shows the possible way of including a heat accumulation unit within the hydraulic circuit of the cogeneration unit using the combustion engine. This type of cogeneration unit can use as a heat source cooling of cylinder head, oil cooler, heat from exhaust gases or a combination of all these sources as is suggested in the proposed schematic diagram.

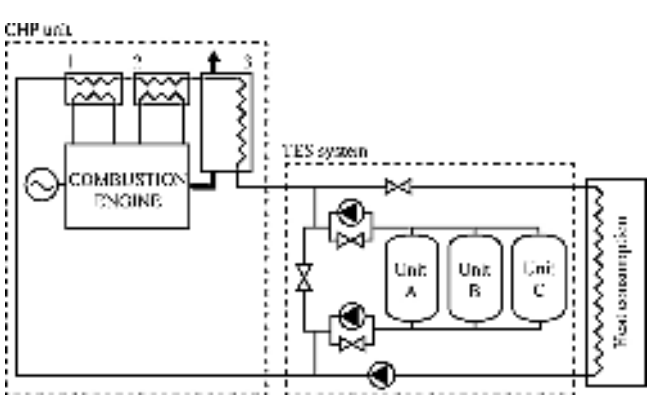

Fig. 9. Proposed schematic diagram of cogeneration unit using heat accumulation units.
(1 – cylinder head cooling, 2 – oil cooling, 3 – exhaust gases heat exchanger).

The basic idea of the technical form of proposed heat accumulation unit is to divide the volume of heat accumulation medium (PCM with metal foam) into partial heat accumulation units, which dimensions will correspond with thermo-technical possibilities and properties of the thus conceived heterogeneous structure. Each heat accumulation unit will operate as a separate functional unit. Therefore, the created spatial matrix must also include the heat exchange surface representing the interface between the heat accumulation unit and the working medium (i.e. cooling medium from cogeneration unit). The last necessary component is an externally operable impulse (initializing) element that ensures the start of the discharge process, when PCM is changing phase from liquid to solid and heat is released.

On the basis of the above, an idea of the technical solution has been proposed where the individual heat accumulation units are in the form of cartridges incorporated into a common casing providing distribution of the heat transfer medium to the individual cartridges. The spatial arrangement of the cassettes in the casing allows the diagonal flow of heat transfer medium across the object.

Each cassette contains a pulse element formed by a piezo actuator (the impulse elements are connected to the electrical system of the device). The heat accumulation units can be connected in a parallel way to the circuit of the heat transfer media in order to achieve the required heat storage capacity.

5. Conclusions

The connection of a heat accumulation unit and a cogeneration unit system is a relatively new technology, which according to literature review brings fuel savings, increases the efficiency of the system, and, last but not least, has a positive impact on the ecological use of the energy source. The presented concept of heat accumulation unit uses a heterogeneous structure of metal foam and PCM that allows accumulating heat without unwanted heat loss in the long period of time.

The uniqueness of the proposed concept is based on the simultaneous use of the metal foam and PCM - sodium acetate trihydrate with sub-cooling effect. Created structure increases the thermal conductivity of PCM which is in case of sodium acetate trihydrate low and it is a limiting factor in thermal applications.

Connection of PCM and metal foam was verified by an experiment simulating the charging phase of the heat accumulation unit with a heat source in the form of a flowing heat transfer medium to achieve analogy with conventional small-scale cogeneration units. The experiment was carried out at the Centre of Renewable Energy Resources on the authors

designed and manufactured measuring apparatus.

The presented results demonstrated the functionality of the heat accumulation unit in the first, charging, phase. At this stage, the heat was successfully accumulated in the form of sensible and latent heat in the PCM, what is reflected in its temperature course, where is visible straight horizontal part at 58 °C, which is characteristic for latent heat accumulation.

The use of the presented heat storage system is also possible in other areas and with other energy sources. The proposed idea of technical solution has been processed into a Utility model application at the Industrial Property Office of the Slovak Republic entitled as "Heat accumulator for the combustion engine."

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