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THERMAL ENERGY STORAGE PROBLEMS

The paper presents the overview of the theoretical and experimental research concerning thermal energy storage problems in the Institute of Heat Engineering.The authors examined a lot of substances which seemed to be suitable for thermal energy storage. The following thermal properties of materials have been measured: melting temperature, latent heat, specific heat vs. temperature for solid and liquid phase and global change of enthalpy for the temperature range of the storage system. Stability of thermal properties (mainly the latent heat) is also a very important property of materials from the viewpoint of thermal storage and has been checked as well. Some characteristics of charging and discharging processes of the single cylindrical vessel and the storage unit with phase change materials (PCMs) are presented in the graphic form. The short description of numerical simulation of Stefan problem (melting and solidification phenomena) will be discussed. The results of numerical calculation of 2-D and 3-D temperature fields for heating and cooling PCM for single vessel and the whole storage unit (i.e. about 60 MJ of thermal capacity) have been compared with experimental results.

Nomenclature

c_p – specific heat
L – latent heat
h – enthalpy
T, t – temperature
τ – time
r – radial coordinate
z – axial coordinate
λ – thermal conductivity
ρ – density
v – velocity of the solid-liquid interface
Q – heat flux

Subscripts

l – liquid
m – melting
s – solid

INTRODUCTION

Why must we store energy? It is necessary to be emphasised that none of the energy sources can be fully satisfying. It is due to:
- time-variable demands,
- time-variable supply of the so-called renewable energy sources, e.g. solar energy and wind power,
- the efficiency of energy conversion and utilisation,
- the concentration of ability to work.

The storage of energy in different forms plays an important role in the effective use of energy. Thermal energy storage (TES) is a very important process in the system of energy utilisation. It can substantially reduce peak power requirement, and also plays an important role in the utilisation of solar energy and heat recovery.

It is necessary to incorporate TES in solar energy and heat recovery systems as there is a temporal mismatch in supply and use of this form of energy.

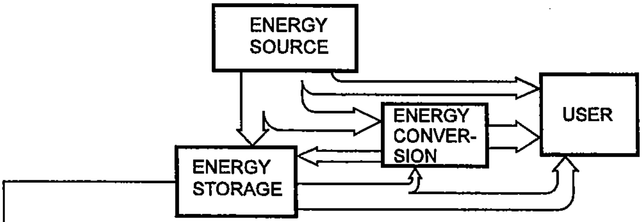
Environmental concern also forces development and implementation of TES systems because they reduce energy consumption and allow the utilisation of some clean sources of energy, e.g. solar.

In this paper we present some results of the investigation of thermal energy storage system with phase change material. In such systems latent heat of materials is used to store energy. It is of primary importance to select a suitable material for the thermal energy storage system under consideration that the phase change takes place in the operating temperature range of the system. The material problems are very important for TES systems. TES with PCM can be used in residential heating (cooling), and also in agriculture – in solar energy systems for drying farmers goods.

Numerical simulation is a very convenient method in the investigations of thermal storage processes, as there are a few advanced numerical techniques to solve the non-linear Stefan problem (heat transfer in PCM). However, experimental tests also give a lot of information about real characteristics of storage systems, especially about overheating and overcooling problems, and a thermal stability problem.

1. ENERGY STORAGE POSSIBILITIES

Energy storage takes a very important place in the source-user system. In many cases there is the necessity of energy conversion between the storage and a user. Figure 1 [1] shows the possible connection between the energy source and an energy user, types of different forms of energy storage and some used materials.



		Energy density MJ/m³	Energy density MJ/kg	Efficiency %	# Cycles
flying wheels		47 - 200	0.05	70 - 85	300 - 3000
compressed air		11 - 40	0.2	65 - 75	4000
hydro-power		0.9	$0.9 \cdot 10^{-3}$	67 - 75	5000
battery (accumulators)		50 - 600	0.2 - 0.4	60 - 80	100 - 5000
fuel cells		< 1800	0.2	35 - 55	
specific heat	sand ΔT=700 K	900	0.7	< 90	
	concrete ΔT=200 K	180 - 340	0.16	85	
latent heat	steam (H_2O)		2.25		∞
	melted salt ΔT=250 K	900 - 1200	0.2 - 0.8		100 - 1500
liquid H_2 production		9000	142		
metals hydrides		10000	0.3 - 11		
other		200 - 300	4.0		
photovoltaic		115 W/m²		8 ÷ 23	
photo decomposition by photons (metals hydrides)				12 ÷ 15	
photo synthesis		4 W/m²		0.5 - 5	
biocatalytical H_2 product					
super conductive systems		~ 100		85	

Fig.1. Energy storage possibilities

The energy can be stored in different forms. One can consider the mechanical energy storage systems, electromechanical energy storage, thermochemical and thermal energy storage, photochemical energy storage, biomass and fuel production. Generally (in literature) energy storage methods may be classified into the following groups [2]:

a) mechanical (physical) methods: hydro-pumped-storage facilities, compressed air (CAES), flywheel energy storage, superconductive magnets,
b) thermal (physical and chemical) methods: heat storage system (solids, liquids, PCM), chemical reaction heat storage (chemical recombination-reversible, chemical-reaction, fuel production),
c) electrochemical (chemical) methods: galvanic cells, batteries, chemical storage (after electrolysis), converters (fuel cells),
d) biochemical storage.

This classification is very rough and can be done in different way.

The basic parameters for energy storage are:

1 – energy density, 2 – input and output power from storage system (time of charging and discharging), 3 – capacity, 4 – number of cycles 1-10000 (for

about 5÷10 years), 5 – working temperature (for some storage systems), 6 – overall efficiency.

The next important problem for the storage system and energy conversion is the value of power density that can be delivered to or withdrawn from a storage unit. The power flux for different systems and units can change from 10^{21} [W/m^2] (high power laser), through 10^{12} (high voltage grid), to 10^6 (heat flux for boiling) and to 10^3 (solar radiation on Earth).

Some main requirements for an ideal storage are:
1 – high storage density, 2 – easy and efficient convertibility to the desired energy form, 3 – low storage loses, 4 – acceptable capital and operating costs, 5 – environmental standards.

The last requirement is perhaps the most difficult to evaluate. The „right price" of the storage must take into account environmental effects.

Energy storage density for different materials and methods is presented in Table 1 [1].

Energy storage is economically attractive when the following requirements are fulfilled:
- reduction of energy consumption,
- reduction of energy costs,
- substitution of another energy source.

The importance of energy storage technologies will increase in particular when time-dependant energy sources will be adopted or time-variable demands will be covered with constant power sources (nuclear power plant).

2. THERMAL ENERGY STORAGE

2.1. Thermal energy storage applications

One of the most important forms of energy storage is a thermal energy storage. It is a physical or chemical process taking place in the store (accumulator) during the charge and discharge operation. The store consists of the storage vessel (usually thermally insulated), the storage medium, the charging and discharging devices, and the auxiliaries. The storage system is defined by the manner in which energy for charging the accumulator is extracted from the energy source and in what form of energy it is discharged from the accumulator and is (in many cases) transformed into the required form of energy. The conversion of energy in a storage unit becomes one of very modern problems in energy storage.

Table 1

Material – Storage Method	kJ/kg
D-D (fusion reaction)	$9.5 \cdot 10^{10}$
^{235}U (fission reaction)	$7.0 \cdot 10^{10}$
Reactor Fuel (UO_2, enrichment 2.5)	$1.5 \cdot 10^{9}$
Hydrogen (C)	$1.2 \cdot 10^{5}$
Methane (C)	$5.4 \cdot 10^{4}$
Propane (C)	$4.6 \cdot 10^{4}$
Crude oil (C)	$4.2 \cdot 10^{4}$
Coal (C)	$3.2 \cdot 10^{4}$
Methanol (C)	$2.2 \cdot 10^{4}$
Trinitrotoluene TNT (C)	$1.9 \cdot 10^{4}$
Dry wood (C)	$1.5 \cdot 10^{4}$
Fuel cell (Apollo)	$3.2 \cdot 10^{3}$
H_2O condensation	$2.3 \cdot 10^{3}$
Melting LiOH	$1.0 \cdot 10^{3}$
Sand heating (ΔT = 700 K)	550
Secondary cell Ag-Zn	440
Melting Al	395
Secondary cell Na-S	360
Freezing H_2O	334
Flying wheels	<300
Heating H_2O (ΔT = 70 K)	300
Melting $C_{28}H_{52}$	255
Sublimation J (iodine)	240
Compressed air	<200
Melting $Ca(NO_3) \cdot 4H_2O$	153
Secondary cell Pb-acid	120
Twisted rubber belts	58
Potential energy H_2O (ΔH = 100 m)	1
Winded watch spring	0.39
Capacitor	0.016

C – combustion

Applications for TES are very wide, from heating and cooling using waste or solar energy, to high-temperature energy storage for power production and industrial processes.

The easiest way for the classification of thermal energy storage possibilities is presented in Fig. 2 [1].

In general, there are three methods of thermal energy storing: sensible, latent, and thermochemical heat storage.

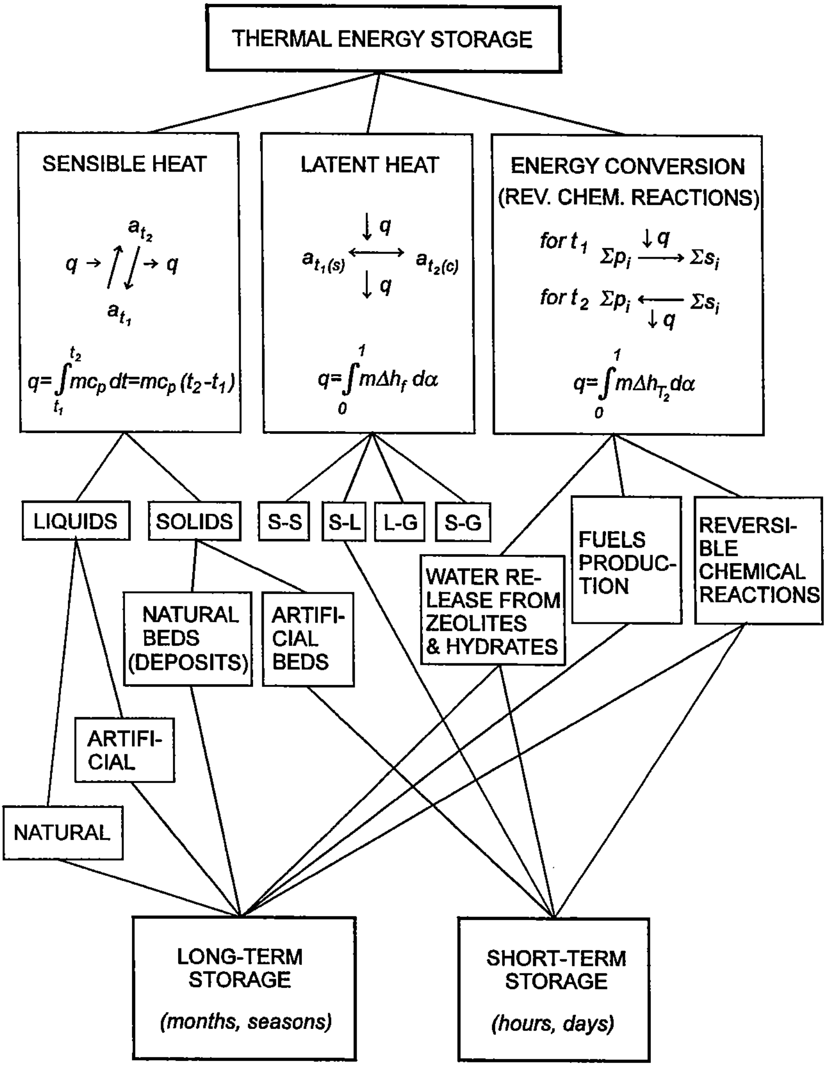


Fig. 2. Thermal energy storage possibilities

In sensible heat storage the quantity of stored heat depends on the temperature change, the heat capacity of the material, and the amount of storing material, see equations in Fig. 2.

In sensible heat storage a solid or a liquid material is being used. Examples for this kind of storage are:

– water tank, aquifer and duct (earth and borehole),
– glycol-water or organic liquid tank with a heat exchanger for a solar collector,
– rock beds (granite with specific heat of 0.8 kJ/kg·K).

Phase change of the material is adapted to store thermal energy in latent heat storage. There is a visible advantage of PCMs (paraffin wax, salt hydrates, and fused salts) over sensible heat storage materials [3].

The last method of thermal energy storage, shown in Fig.2, is the thermochemical heat storage which includes reversible chemical and photochemical reactions, water release from zeolites and hydrates and fuel production. The advantages of this method are: more compact system, long-term and room-temperature storage.

Another TES classification is short or long-term (seasonal) storage. There are some long-term storage systems under operation, resting on natural bases (aquifers, rocks, caverns, lakes) or artificial ones (insulated tanks, ponds, rock boreholes). The primary application area of such systems are heating and cooling of large buildings and industrial processes cooling [4]. This paper concerns only short-term TES with PCMs.

The temperature range for several important storage materials is presented in Fig.3 [1].

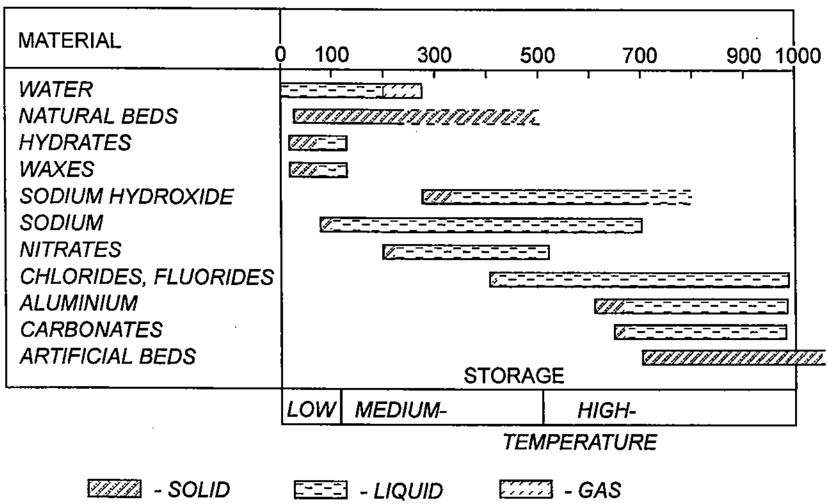


Fig. 3. The temperature range for some storage materials

2.2. Material problems – experimental equipment and results

Attention must be paid to the selection of suitable materials for thermal energy storage, particularly when latent heat is utilised. We must consider five general selection criteria for PCM: thermal, physical, kinetic, chemical and economic. In particular, the following factors are discussed:
– phase transition temperature, latent heat of fusion, heat transfer,
– phase separation, vapour pressure, volume change, density,
– supercooling and crystal growth,
– chemical stability, safety,
– availability, cost-effectiveness.

It is necessary to have full information about thermophysical properties of materials under consideration. This includes melting point temperature (or temperature range in which change of phase occurs), specific heat, enthalpy vs. temperature, thermal conductivity and, what is most important, stability of thermal properties in succeeding cycles of heating and cooling.

In order to determine the thermal properties of materials in the wider range of temperature than it is possible using the classical measurement equipment, the special investigation stands have been set up. In our Institute we have constructed investigation equipment allowing us to determine specific heat of solid and liquid materials, latent heat and enthaply as a function of temperature and also to investigate the stability of thermal properties in heating and cooling cycles.

In our investigation of thermal storage processes the following equipment were used:

- standard differential scanning calorimeter (DSC) – for fast measurements of specific heat, temperature of fusion and latent heat. This calorimeter was used for crystalline and pure materials [5],
- special equipment (made in the Institute of Heat Engineering) to evaluate the characteristics of enthalpy vs. temperature for samples of relatively big mass (from 20 to 50 g). This equipment can be used for any material, the purity of which can be lower than for DSC,
- special equipment for investigation of stability of thermal properties in succeeding cycles of heating and cooling (melting and crystallization) for samples of a mass from 250 to 500 g. For some materials more than 1000 cycles were performed.

Some measurements have been made using DSC-7 calorimeter (Perkin-Elmer). Basic parameters of this equipment are:

- temperature range 50÷730°C
- accuracy of temperature measurements 0.1°C

– scanning rate 0.1÷200°C
– calorimetric precision 0.1%
– possibility of carrying on measurements in protective atmosphere of inert gas.

Using DSC calorimeter we have identified thermodynamic and physical properties of a large number of PCMs. Some examples:

– waxes: PPW20 and Rew-II,
– n-alkanes (e.g. Eicosanol, Octacosane, Octadecane),
– benzoic acid,
– eutectic mixture (e.g. $NaNO_3$-NaOH).

Figures 4÷9 show DSC heating curves for this materials. Latent heat is rather high: from 135 to 258 kJ/kg. The eutectic mixtures seem to be very

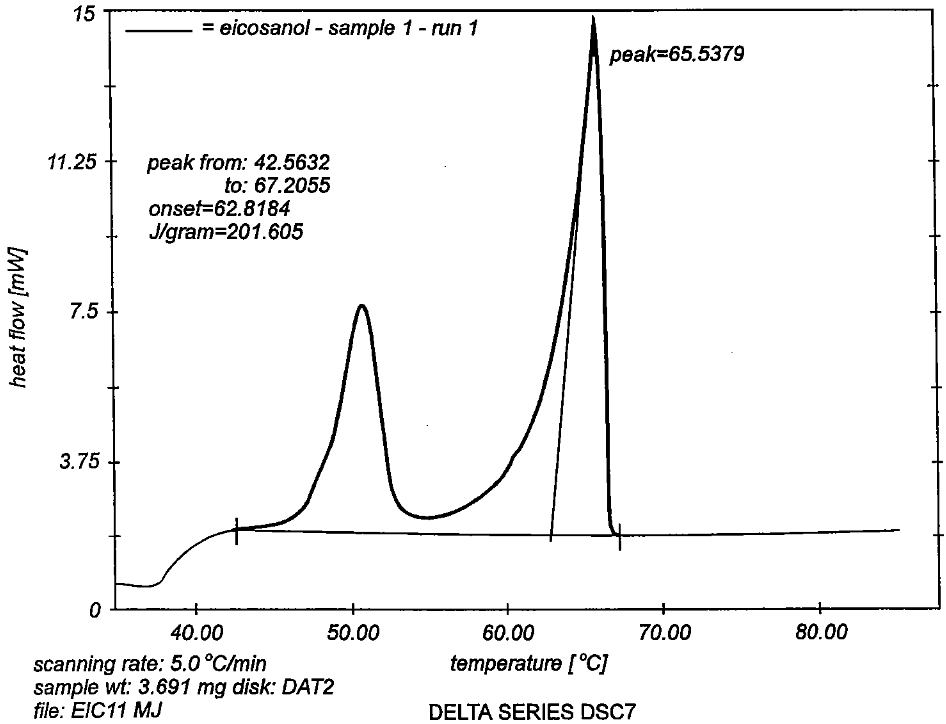


Fig. 4. The results of the measurement of temperature and specific heat of Eicosanol

interesting and we have investigated other eutectic mixtures (59 and 81.5% mol NaOH). Some of investigated materials (e.g. waxes) turned out to be suitable for TES, especially for solar systems with plate collectors.

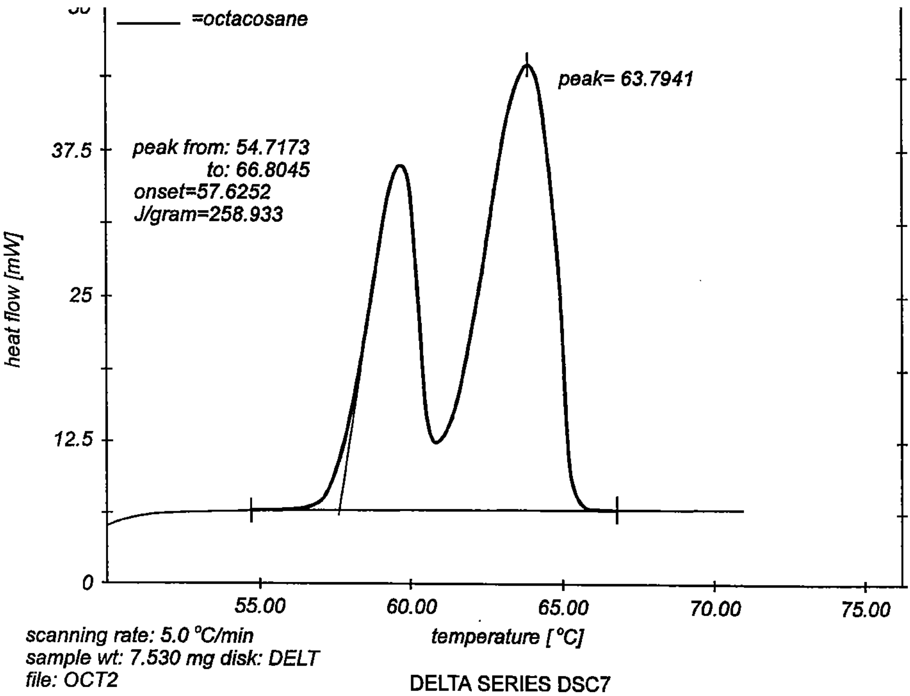


Fig. 5. The results of the measurement of temperature and specific heat of Octacosane

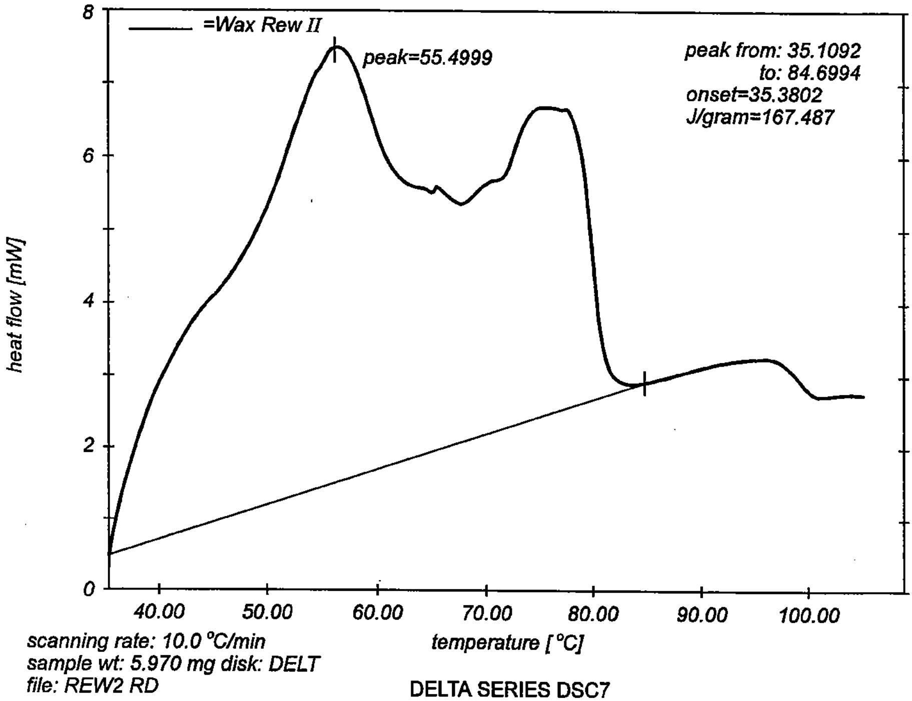


Fig. 6. The results of the measurement of temperature and specific heat of wax Rew-II

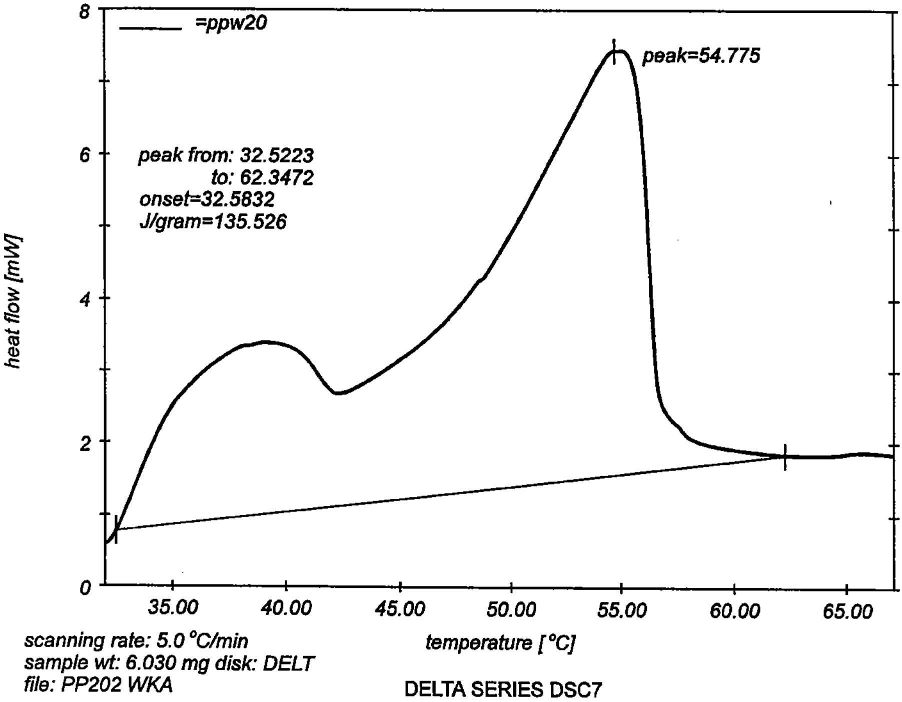


Fig. 7. The results of the measurement of temperature and specific heat of wax PPW20

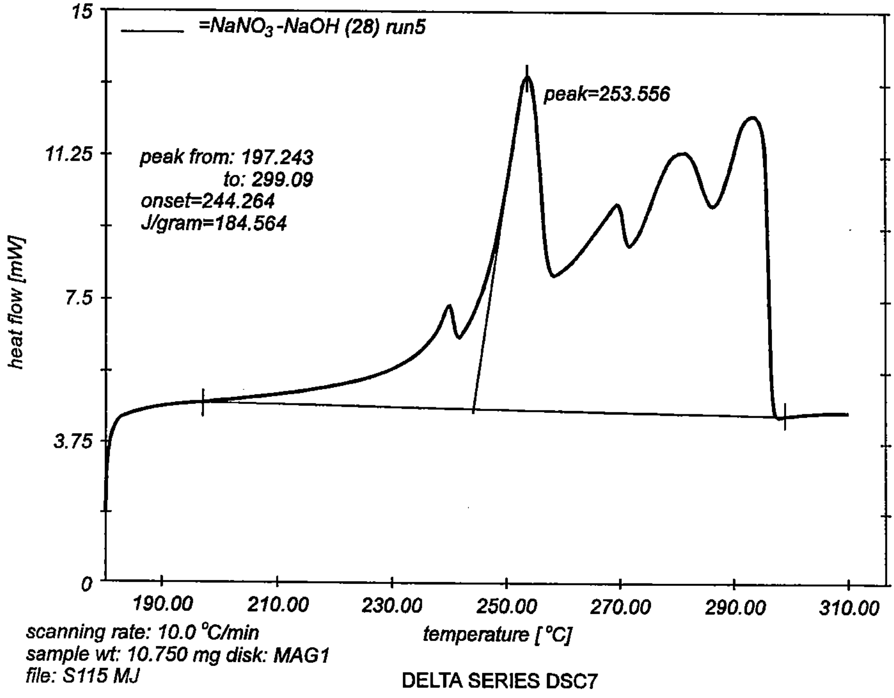


Fig. 8. The results of the measurement of temperature and specific heat of eutectic mixture $NaNO_3$-NaOH

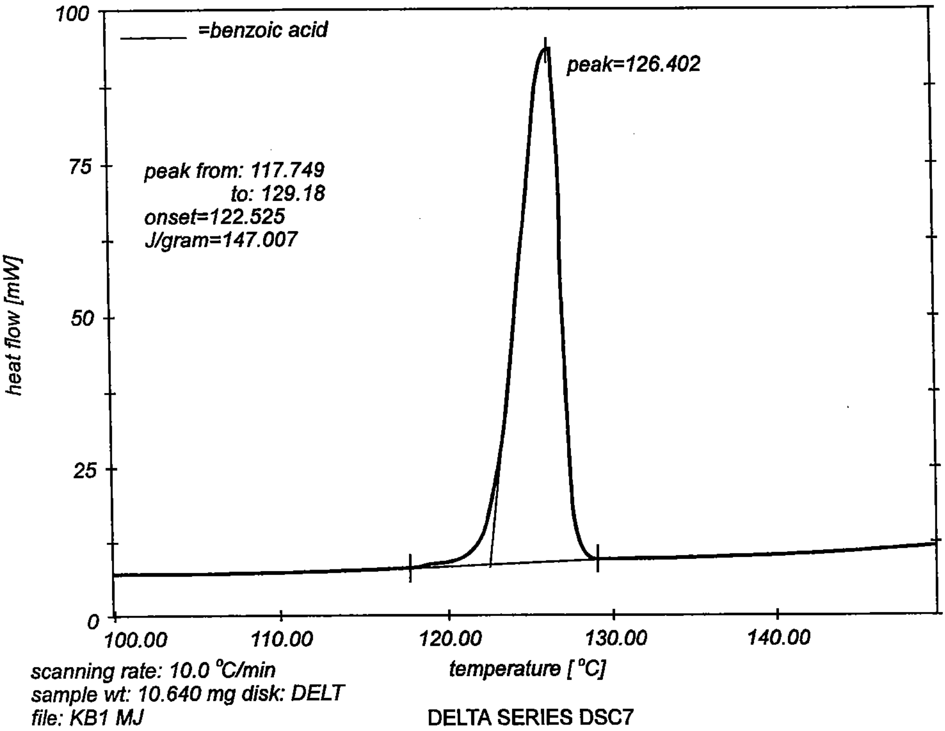


Fig. 9. The results of the measurement of temperature and specific heat of benzoic acid

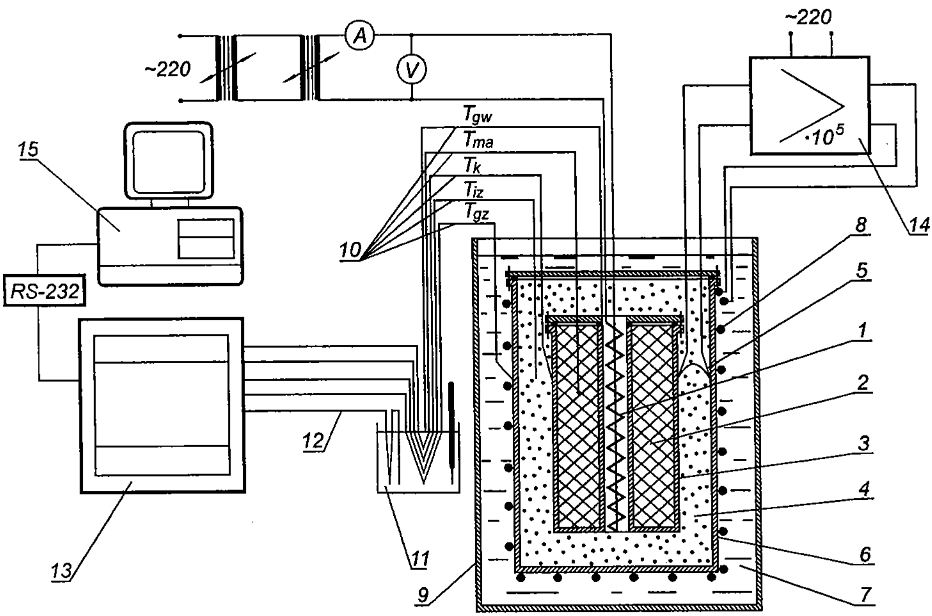


Fig. 10. The special equipment for measurements of the PCM characteristic

Fig.10 shows a scheme of a stand for measurements of specific heat, latent heat, enthaply as a function of temperature (in the range 300÷800 K), samples mass 20÷50 g (volume of a vessel about 130 cm^3). An investigation material (2) closed in a calorimeter's vessel (3) is heated with constant power by a heater (1). The temperature in different points is measured by sheathed thermocouples with an outside diameter 0.5 mm. The loss of heat to environment is minimized by an external heater (8) the power of which is controlled by differential thermocouples (5) and an amplifier (14). The stand was calibrated, characteristics of the heat flux to environment as function of a difference between the calorimeter temperature T_k and the temperature T_{gz} on the external shield were determined. The temperature was measured by a multichannel recorder (13) or an IBM PC computer with the ADDA card and the amplifier/multiplexer board (15). It is possible to determine specific heat and enthalpy by using this equipment during the measurement [5].

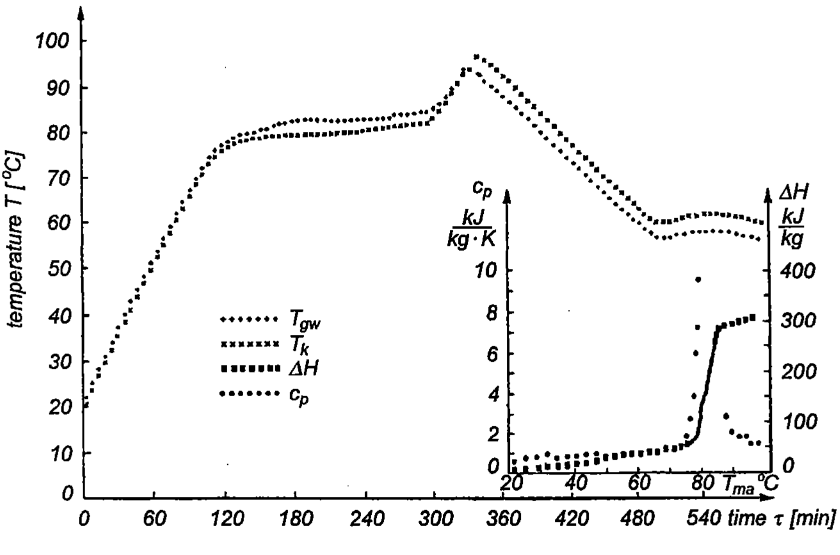


Fig. 11. The characteristic of specific heat and enthalpy measured at a special stand

Figure 11 [1] shows results of measurements on this stand. The main part of the figure shows temperatures in two different points, in the right-bottom corner specific heat and enthalpy as function of temperature are presented. The measured substance was barium hydroxide. Additionally the temperature and latent heat is estimated, the overcooling is apparent during the cooling. Positions of thermocouples in the calorimeter allow to determine the temperature characteristic in the investigated material (along the radius of the sample's tube) and it allows to determine the thermal diffusivity of the solid material [6]. Over 50 different materials have been examined by using this stand: organic materials, hydrate salt, mixture of salts as well as eutectic mixtures [6, 7].

Functional characteristics (polynomials) for enthalpy as a function of temperature which are very useful in the modelling of heat transfer processes (heat storage) were determined [1].

Figure 12 [1] shows experimental results of enthalpy measurement for some chosen PCMs.

The stability of thermal properties of some materials was determined by a very similar stand in heating and cooling cycles, volume of the main part of the calorimeter allows to test samples about 500 g [6]. Results of these measurements are consistent with literature data. Figure 13 [1] presents results of temperature measurements for 1st, 13th and 28th heating and cooling cycles for hydrates: $Na_2S_2O_3 \cdot 5H_2O$ (sodium thiosulphate). It turned out that this material decomposed and there was no phase change during the last cycle (doted line) – chemically unstable material.

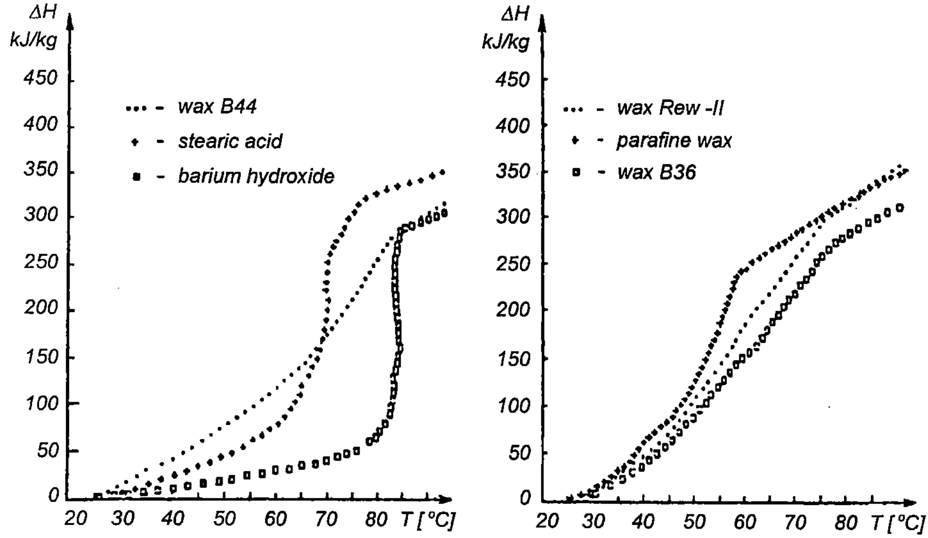


Fig. 12. The experimental results of enthalpy measurement for some chosen PCMs

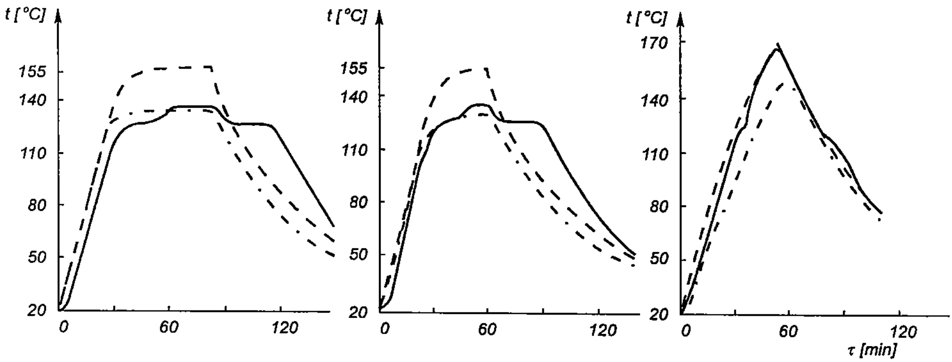


Fig. 13. The results of temperature measurements for hydrates: $Na_2S_2O_3 \cdot 5H_2O$ during heating and cooling cycles

2.3. Thermal energy storage unit

A special experimental stand was developed to determine the temperature distribution inside a thin-wall tube with PCM (see scheme in Fig. 14). Such measurements gave information about temperature gradients in PCM during heating and also about conditions in which free convection in melted region occurs.

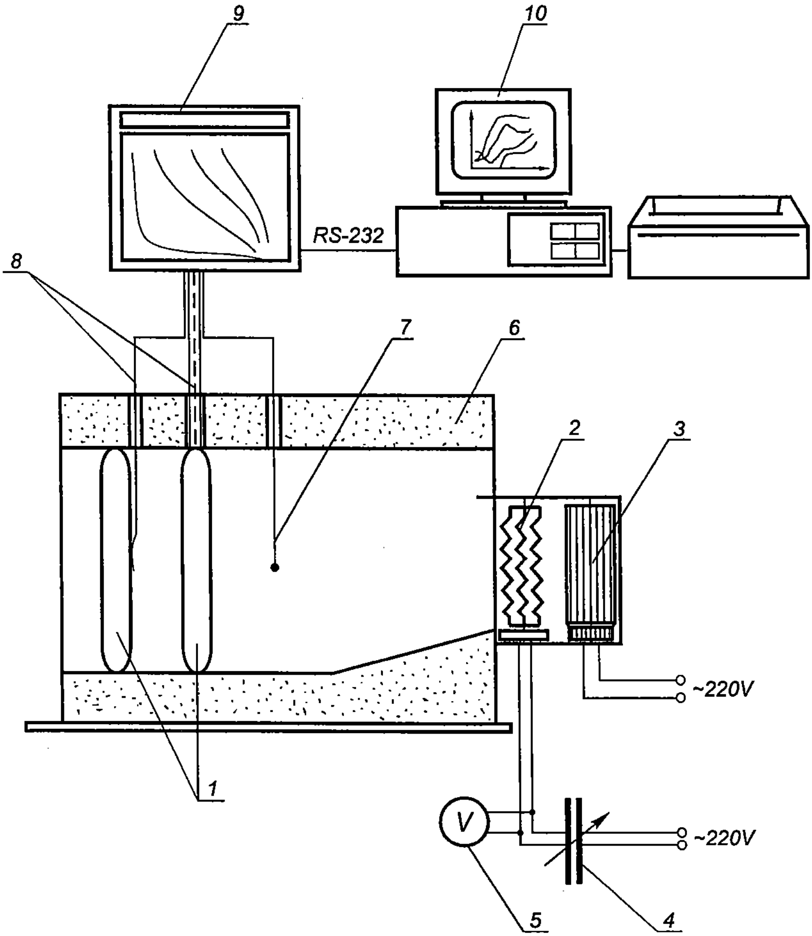


Fig. 14. The experimental stand for investigation of a single PCM element

An investigated PCM (wax) (1) closed in a tube is heated or cooled by an air flow; (2) – a heater, (3) – a fan. The temperature of a material and of the air is measured by thermocouples (7,8) connected with a multichannel recorder (9) or an IBM PC computer with the ADDA card and the amplifier/multiplexer board (10). Series of experiments were performed for both charge and discharge modes (discharging by cold air) under conditions of different air flow rates, air temperature, initial temperature of PCM. The temperature distribution on radial and axial direction was measured during heating and cooling. Figure 15 shows the temperature rise during heating by air of 90°C temperature. We can observe an effect of free convection (very fast rise of temperature in a melting area).

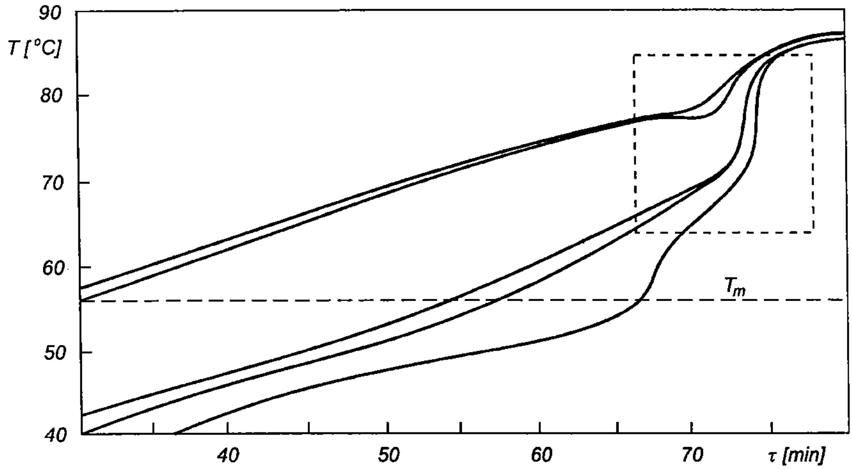


Fig. 15. The temperature rise during heating by air of 90°C temperature in a single PCM element

A small-scale latent thermal energy storage unit was developed. A scheme of the unit is shown in Fig. 16 [8]. The phase change material (PCM) is enclosed in vertical tubes, made of polyethylene of 0,1 mm thickness. Each element is 850 mm height, 41 mm in a diameter and contains about 0.95 kg of PCM – in this case wax PPW-20. There can be from 190 to 220 elements in the unit. For the number of elements 190 (i.e. about 180 kg of wax) thermal capacity of the unit is estimated to be about 60 MJ (on the basis of measurement of enthalpy changes in the temperature range from 20 to 95°C).

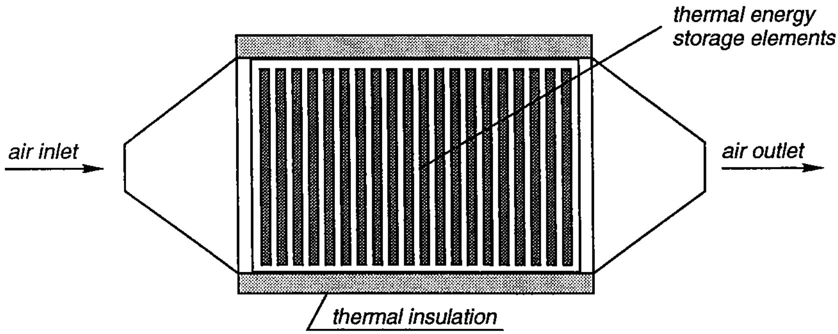


Fig. 16. Scheme of the thermal energy storage unit with a phase change material

Thermal energy storage of presented design can be used for solar energy utilisation, with air as the heat transfer fluid. Operation temperature range is relatively low (melting point of wax PPW-20 is about 56°C).

A series of experiments were performed for both the charge and discharge modes under conditions of different temperature and flow of heat transfer fluid (air). In Fig. 17 [7] temperature of the PCM in selected rows (solid lines) and temperature of air at the inlet, in the middle and at the outlet (dashed lines) are presented. This illustrates the charging characteristic of the unit at air flow of about 0.208 kg/s.

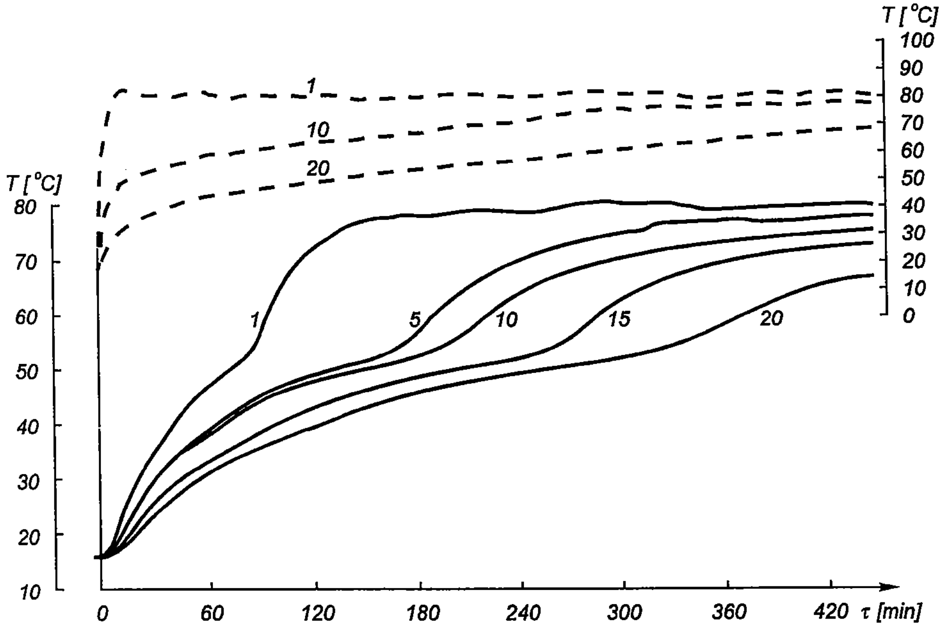


Fig. 17. Temperature of the PCM in selected rows of elements and temperature of air (heat transfer fluid) during charging thermal storage unit

In Fig. 18 [8] another characteristic of the unit (for discharging) is presented. It shows the decrease of temperature as a function of time during the discharging process. Numbers near lines depict first half of the unit (1), the second half (2) and the whole unit (1+2). As the flow of air is constant during the process, these lines show the changes of energy released from the unit as a function of time.

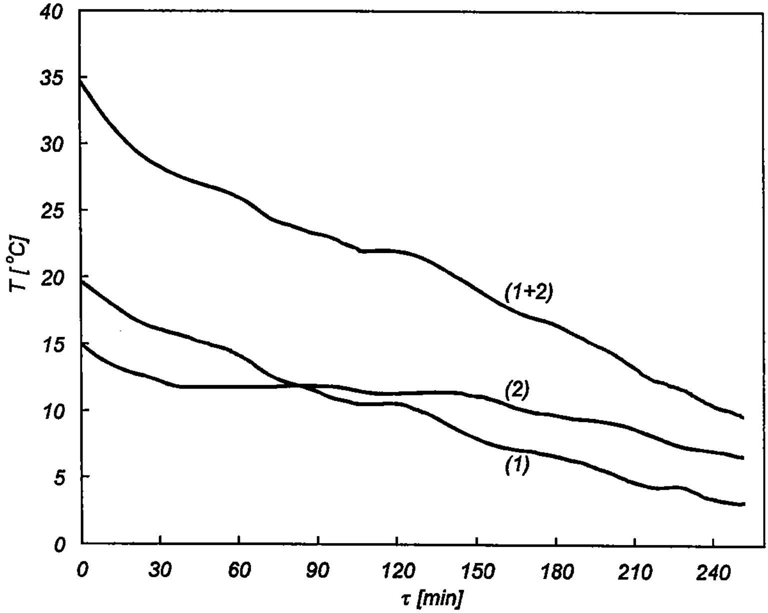


Fig. 18. Decrease of temperature of the heat transfer fluid (air) during discharging process

2.4. Numerical simulation of thermal energy storage in PCM and a storage unit

The experimental research is very expensive. The main purpose of a computer simulation of physical processes which take place in thermal storage systems is to obtain characteristics of such systems very quickly and at low costs. Numerical simulation of charging and discharging processes of thermal storage system is based on solving energy equation (with proper boundary and initial conditions) for the given geometry of the whole system and individual elements containing phase changing material. A computer program for determining the temperature fields of PCM and heat transfer fluid in the unsteady state of charging and discharging thermal storage unit has been prepared.

Mathematical formulation

To determine the temperature fields in the unsteady state in a vertical tube with PCM it is necessary to solve heat balance equations (for the cylindrical 2-D geometry) that describe the heat transfer during phase change:

– in the liquid phase $T > T_m$:

$$\rho_l \frac{\partial(c_{pl}T)}{d\tau} = \frac{\partial}{\partial z}\left(\lambda_l \frac{\partial T}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial t}\left(\lambda_l r \frac{\partial T}{\partial r}\right) \qquad (1)$$

– in the solid phase $T < T_m$:

$$\rho_s \frac{\partial(c_{ps}T)}{d\tau} = \frac{\partial}{\partial z}\left(\lambda_s \frac{\partial T}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_s r \frac{\partial T}{\partial r}\right) \tag{2}$$

– at the solid/liquid interface (Stefan problem)

$$\lambda_l (\boldsymbol{n}\,\mathrm{grad}\,T)\big|_l - \lambda_s(\boldsymbol{n}\,\mathrm{grad}\,T)\big|_S = \rho_m L_m \mathbf{v}\boldsymbol{n} \tag{3}$$

Initial condition:

$$T(r,z,0) = T_0 = \mathrm{const}, \quad \text{for } \tau = 0 \tag{4}$$

Boundary conditions (between storage tube and air flow):

– for cylindrical surface:

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=R} = \alpha_r\big(T(R,z,\tau) - T_\infty(\tau)\big) \tag{5}$$

where: α_r – the heat transfer coefficient for cylindrical surface, T_∞ – air temperature;

– for front surface:

$$-\lambda \left.\frac{\partial T}{\partial z}\right|_{z=\frac{H}{2}} = \alpha_h\left(T\left(r,\frac{H}{2},\tau\right) - T_\infty(\tau)\right) \tag{6}$$

where: α_h – the heat transfer coefficient for frontal surface.

Air temperature behind a row of PCM tubes, which changes during the flow along the storage unit, can be determined from energy balance equitation (for air):

$$\alpha S\big(T_\infty - T_{\mathrm{wall}}\big) = w_v \rho_\infty c_{p\infty}\big(T_{1\infty} - T_{2\infty}\big)$$

where: w_v – flow rate of air for one element in a row [m^3/s], ρ_∞ – air density, $c_{p\infty}$ – sensible heat of air, S – an element surface, $T_{1\infty}$ and $T_{2\infty}$ – air temperature before and after the element, T_∞ – average air temperature $\big(T_{1\infty} + T_{2\infty}\big)/2$, α – the heat transfer coefficient which is determined by the relation:

$$\alpha = \frac{\mathrm{Nu}\,\lambda_\infty}{D_h}$$

where: Nu – Nusselt number, λ_∞ – air conductivity, D_h – hydraulic diameter.

Nusselt number is calculated from empirical relations.

In the balance equation for heat transfer fluid, the heat losses for the whole unit are considered.

In the energy balance equation the convection in the melted zone was not taken into account.

Numerical method

From several ways of solving the problem presented above in mathematical formulations, enthalpy balance method – a finite difference numerical discretization and explicit temporal discretization scheme – was chosen. The processes of phase change (solidification and melting) are nonlinear in the mathematical sense due to a moving solid/liquid interface. The solution of this problem is much more difficult when thermal properties of PCM (λ, c_p) are temperature-dependent and when the boundary conditions apply to convection.

The first step in the computional process is to subdivide an investigated tube into a definite number of small balance elements. The differential grid consists of ($NI \cdot NJ$) nodal points – where NI is a number of nodal points along a radius of the tube, NJ is a number of nodal points along z coordinate. The nodal point of a differential grid is located inside the balance element. The shape of a balance element is annular: inside diameter $RS(I)$, outside diameter $RN(I)$ and height $\Delta Z(J)$. I and J indicate positions of balance elements (nodal points) in a differential grid. Fig. 19 [9] shows the shape of the balance element and a part of the differential grid. The temperature in particular nodal points of a grid (average temperature in balance elements) at time τ can be obtained from

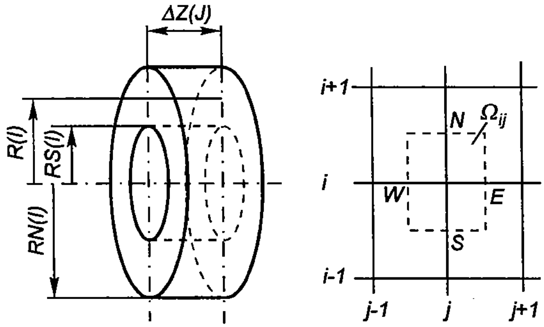


Fig. 19. Scheme of the balance element and the part of the grid pattern used in the numerical solution

$$T(I,J) = f(h(I,J))$$

A form of the function f depends on changes of a specific heat with temperature and a time history of a phase change process – in general this process takes place in a temperature interval $T_m \pm \Delta T_m$.

In the enthalpy formulation equations (1) and (2) can be reduced to a single equation

$$\rho \frac{\partial h(T)}{d\tau} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) \tag{7}$$

where: $h(T)$ – an enthalpy function (the sum of latent and sensible heats)

$$
h = \begin{cases} \int_{T_0}^{T} c_{ps}(T)dT & T < T_m - \frac{\Delta T_m}{2} \\ \int_{T_0}^{T_m} c_{ps}(T)dT + \frac{T - T_m + \Delta T_m/2}{\Delta T_m} C_m & T_m - \frac{\Delta T_m}{2} < T < T + \frac{\Delta T_m}{2} \\ \int_{T_0}^{T_m} c_{ps}(T)dT + C_m + \int_{T_m}^{T} c_{pl}(T)dT & T > T_m + \frac{\Delta T_m}{2} \end{cases}
$$

The enthalpy of a balance element (I, J) at time τ is obtained from a balance of a heat flux at the boundary:

$$
h(I,J)_{\tau} = h(I,J)_{\tau - \Delta\tau} + \frac{\Delta\tau \left(Q_R + Q_Z\right)}{\rho \, \Delta Z \pi \left(RN(I)^2 - RS(I)^2\right)} \tag{8}
$$

where: $\Delta\tau$ – time interval, Q_R – heat flux at the boundary along a radius, Q_Z – heat flux at the boundary along z coordinate [9].

Relations presented above apply to inside elements. Changes of enthalpy in boundary elements must be determined with boundary conditions.

In the calculations thermal properties of storage materials were taken from the measurements, especially characteristics of enthalpy vs temperature.

3.4.3. Numerical results for a single vertical tube and thermal storage unit with PCM

With numerical techniques different heat transfer problems were simulated – charging and discharging of the whole unit as well as 3-D temperature field in single elements with PCM of different geometries.

Figure 20 is an example of the numerical charge test of a single vertical tube of diameter 0.041 m, filled with PCM (wax PPW-20, melting point 56°C).

Lines show the temperature distribution in radial direction for different times from the beginning of the process. For this case the tube is heated by air of temperature 95°C, heat transfer coefficient on the surface is 18 W/(m^2·K).

Results of numerical simulation of charging single elements of thermal storage system show, among others, that there are rather high temperature gradients in the PCM up to the time when material is completely melted. It is a result of rather small thermal conductivity of this kind of materials (for PPW-20 it is about 0.8 W/(m·K)).

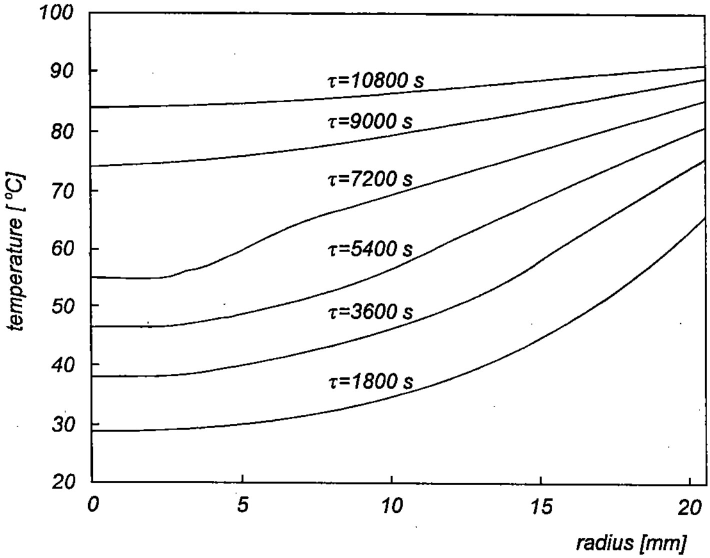


Fig. 20. The example of the numerical charge test of a single vertical tube with PCM

Figure 21 shows results of numerical simulation of charging process of the thermal storage unit with wax PPW-20. In this case cylindrical elements of dimension 20 mm were considered, there were 42 rows of elements, air flow was 0,21 kg/s, temperature of air at the inlet was 85°C.

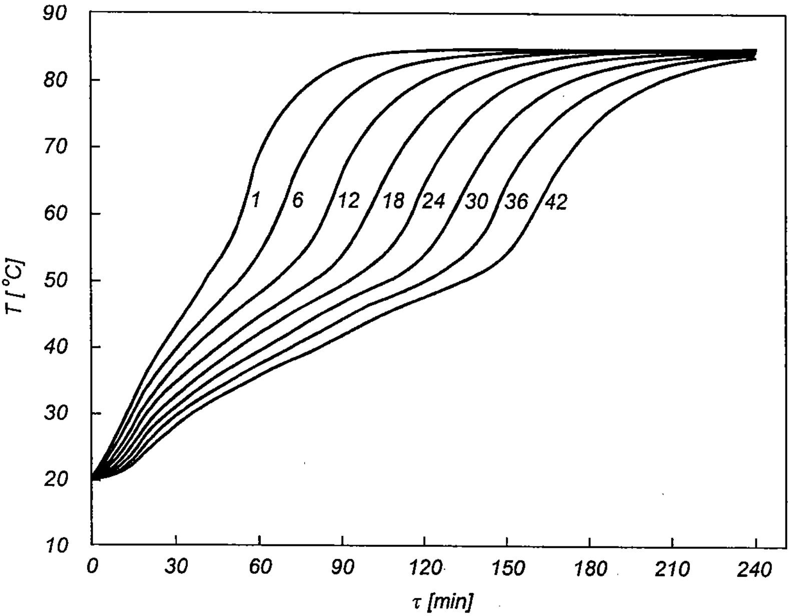


Fig. 21. Temperature in selected rows of elements with PCM during charging thermal storage unit – results of numerical simulation

The results of the numerical simulation for chosen materials were compared with the experimental data for a single element and the whole storage unit.

This analysis showed a strong correlation between numerical and experimental results.

CONCLUSIONS

Experiments carried out in our Institute gave some new information about thermal storage processes. First of all our investigation concentrated on testing thermal properties and stability of PCMs. Using DSC and other special equipment we were able to measure specific heat, temperature of fusion and latent heat as well as to evaluate the characteristics of enthalpy vs temperature for both small (mg) and relatively big (20-50 g) samples of different materials. Data obtained from our experiments enables us to establish the usefulness of these materials for the thermal energy storage.

In order to determine the main parameters of TES system (such as its dimensions, mass of PCM, flow rate of heat transfer fluid and so on), we tested the temperature time history for charging and discharging, and temperature gradients in single elements of the storage unit of different dimensions and geometries.

Basing on our results, we constructed the thermal storage unit consisting of 200 vertical tubes of PCM. This storage unit was regarded both as an element of recovery and utilisation of waste thermal energy and an element of solar energy system with plate collectors with air as a medium.

The comparison of experimental and computer simulation results let us verify the mathematical and numerical model of multidimensional heat transfer problems (including the change of phase). Numerical procedures, solving complex heat transfer problem, were used to develop a computer program which is useful for designing energy storage systems with PCM.

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Streszczenie

W artykule zaprezentowano przegląd prac teoretycznych i badawczych dotyczących problemów magazynowania energii cieplnej podjętych w Instytucie Techniki Cieplnej Politechniki Warszawskiej.

Autorzy przebadali szereg materiałów pod kątem ich przydatności w magazynowaniu energii cieplnej. Wyznaczano następujące właściwości cieplne materiałów: temperaturę topnienia, ciepło przemiany fazowej, ciepło właściwe w funkcji temperatury dla fazy stałej i ciekłej oraz całkowitą zmianę entalpii dla zakresów temperatury pracy systemów magazynujących. Zbadano stabilność właściwości cieplnych materiałów magazynujących (głównie ciepła przemiany fazowej).

Zaprezentowano wykresy charakterystyk procesu ładowania i rozładowania dla pojedynczego cylindra i modułu magazynującego wypełnionego materiałem ulegającym przemianie fazowej (PCM).

Przedstawiono krótki opis symulacji numerycznej problemu Stefana. Porównano wyniki obliczeń numerycznych oraz wyniki eksperymentalne dla dwu- i trójwymiarowego pola temperatury dla grzanego i chłodzonego materiału (PCM) w pojedynczym cylindrze i module magazynującym (pojemność cieplna około 60 MJ).

ПРОБЛЕМЫ АККУМУЛЯЦИИ ТЕПЛОВОЙ ЭНЕРГИИ

Краткое содержание

В работе дан обзор теоретических и экспериментальных работ Института теплотехники, посвященных вопросам аккумуляции тепловой энергии.

Авторы исследовали материалы с точки зрения их пригодности для аккумуляции тепловой энергии. В работе исследуются изменения удельной теплоемкости и энтальпии в зависимости от температуры, а также изменения тепловых свойств материалов в результате многочисленных циклов плавления.

Для накопителя использующего фазовое превращение в вычислениях использовались результаты экспериментальных исследований материалов.