



## CELLULAR METALS AND COMPOSITES FOR AN OPTIMISATION OF THE LOADING AND RE-LOADING BEHAVIOUR OF THERMAL STORAGES

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### MOTIVATION

Thermal energy storages today play a significant role in power engineering processes and become more and more important especially with respect to the increasing use of renewable energy sources. Depending on the special technical application and the required loading and re-loading regimes a reasonable division of such devices into thermal storages and thermal buffers is possible.

**Heat storages** are used to compensate time differences between supply of heat and its demand. Regarding to renewable energies especially local solar thermal applications in apartment houses are of interest. While the maximum efficiency of energy absorption is at noon, the demand of heat in the household is mainly concentrated on the morning and evening hours.

Even in the field of energy efficient technologies thermal storages play a decisive role because of the fact that the transformation on heat into other types of energy mostly is inefficient from an exergetic point of view. In contrast its storage – assuming a later heat demand – is more effective. Some examples for such applications are the use of waste heat of a combustion engine to prevent the next cold starting or the use of heat from an exothermic reaction to support a subsequent endothermic one. Required scenarios of loading and re-loading procedures depend on the special application.

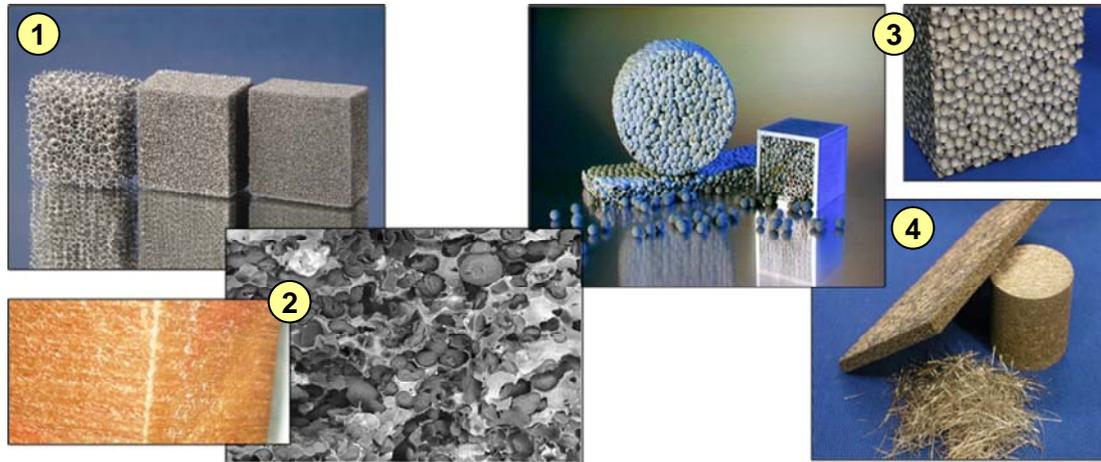
The heat capacity of **thermal buffers** is – in contrast to storages – mostly used to damp peaks of thermal loads to cool heat generating devices (without re-use of the heat). Some examples are components of power electronics with cyclic heat generation and high-power-batteries to store electric energy from the deceleration of a car, respectively. In these cases usually very short loading and re-loading periods have to be realised under difficult thermal conditions.

Thermal storages with high volumetric energy densities are only practicable using phase change materials (PCM – water, paraffin, salt hydrates). Thermal storage is based on so-called latent heat represented by the melting enthalpy of the used material at a nearly constant temperature – the melting temperature. In the case of a melting temperature higher than those of the surroundings it is called heat storage, otherwise – below the surroundings temperature – cold storage. From a thermodynamic point of view it's of course an identical procedure.

To get a tailored dynamics of loading and re-loading of the storage two parameters have to be optimised: firstly the inner surface between PCM and the heat transfer medium and secondly the heat conductivity of the PCM. For these purposes cellular metals and composites developed at Fraunhofer IFAM Dresden show intelligent approaches.

## APPROACH

The **improvement of the thermal conductivity** of a PCM is possible in an optimal manner by means of inserting a metal matrix. For this reason metallic foams filled with PCM, fiber or wire structures as well as metal-PCM composites are qualified. As lower the porosity of these materials (volume of PCM related to total volume) as higher its resulting effective heat conductivity, but – of course – as lower is the remaining heat capacity.



**Figure 1 Cellular metals and composites for thermal energy storage**

A choice of cellular materials developed at Fraunhofer IFAM Dresden which are applicable as **heat conducting matrix** is shown in Figure 1. Foam (1), fiber (4) and wire structures are manufactured from different materials (stainless steel, aluminium, copper, nickel, alloys) with open porosities up to 97 %. In contrast composites [copper-PCM (2)] usually have porosities in the range of 40 up to 60 %, but with remaining effective heat conductivities of 25 % related to the solid metal. An advantage especially of composites and fiber structure is that the PCM even in a molten state is fixed by means of capillary forces.

An increase of the **inner surface** between heat transfer medium and PCM is realisable by decreasing the size of the PCM-capsules. The volumetric inner surface of a spherical packed bed is inversely proportional to the sphere diameter at a constant porosity. Metallic hollow spheres [(3) in Fig. 1] can be manufactured with a wall thickness in the range of micrometers and later filled with a PCM because of its porous shell. A subsequent sealing of the shell is possible (due to special coatings) but mostly not necessary. Hollow spheres filled with PCM are applicable as single spheres in heat transfer liquids (as “swimming” heat capacities) or alternatively as structure (packed bed) with a liquid or gas flowing through the open pores.

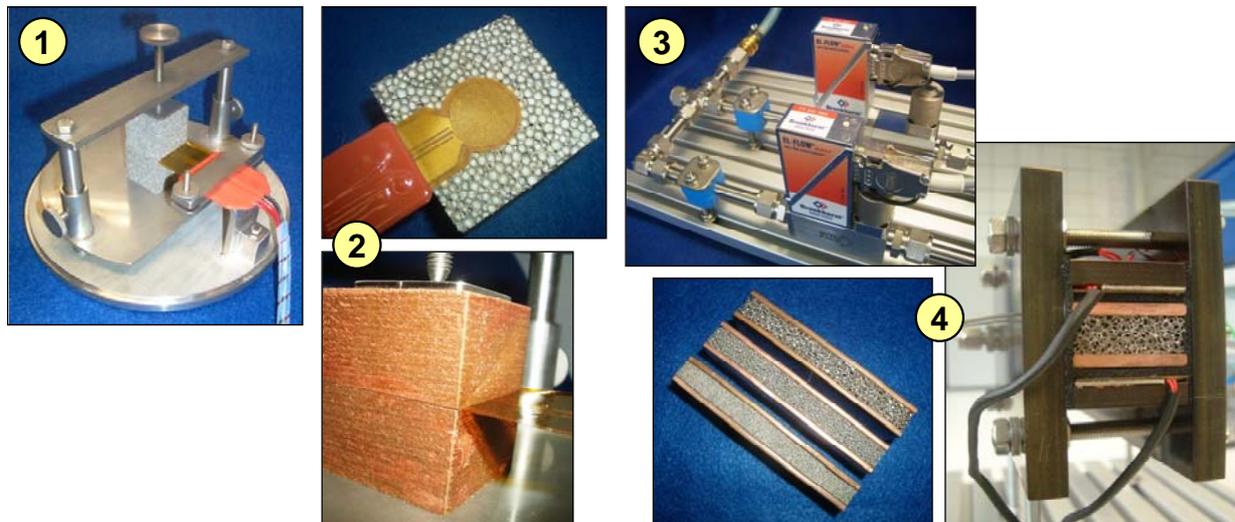
At Fraunhofer IFAM Dresden not only competencies in material development and manufacturing of cellular metals and metal-matrix-composites with tailored properties are available. The business segment Energy and Thermal Management additionally provides detailed know-how for thermal and flow design of thermal storages based on long-time experiences in the field of heat and mass transfer research.

## TRANSPORT COEFFICIENTS

A basic requirement for qualified design calculations is the knowledge of the effective **state and transport properties** of the – however in detail structured – metal-PCM-composites. The resulting heat capacity is simply found from tabulated values of the solid metal and the used PCM if the porosity is known or measured. This includes the consideration of the phase change (latent heat). Much more complicated is the determination of the resulting heat conductivity of a metal-PCM-composite or the measurement of heat transfer and pressure loss coefficients in the

case of a fluid flowing through an open-cellular structure. These transport coefficients only can be determined using experimental methods and generalised empirically based on geometrical parameters of the cellular structure. For this purposes the thermotechnical laboratory at IFAM Dresden is optimally prepared.

To measure the **heat conductivity** steady-state and transient methods are known. Presently the so-called hot-disk-method is used, whereas a flat sensor is positioned between two identical samples of the material and heated. From the measurement of the time-depending sensor temperature the heat conductivity of its surroundings (= samples) is calculated. This method definitely is qualified also for cellular materials. The only condition which has to be fulfilled is to ensure a planarity of all surfaces in contact to the sensor (manufactured for instance by means of wire eroding). Figure 2 shows the sample holder of the hot-disk-device (1) with clamped fiber samples, a hot-disk-sensor in front of a hollow sphere sample [upper part of (2)] and a sensor configuration between two copper-PCM-composites [lower part of (2)], respectively.



**Figure 2** Measuring equipment to determine transport coefficients of cellular materials and composites

The 2d-anisotropic heat conductivity of fiber structures is determined during a single measurement using a special evaluation procedure. The measuring results of the heat conductivity (mostly without PCM) are described empirically using a thermal resistance model depending on the porosity. These mathematical relations later are used for optimisation calculations of thermal energy storages.

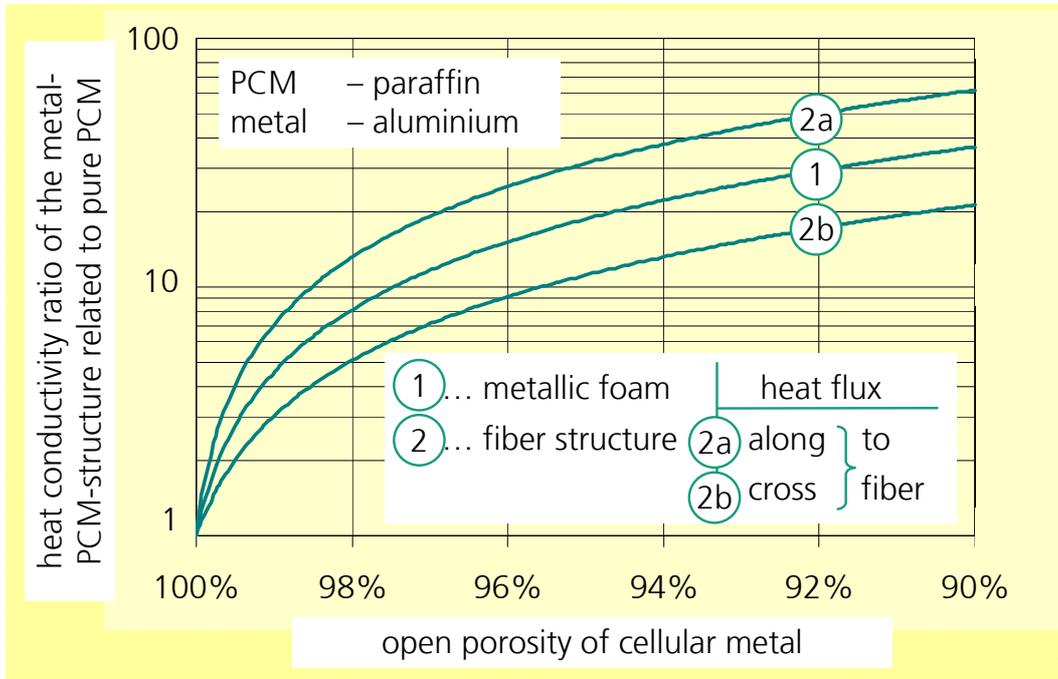
Additionally **thermal contact resistances** between a cellular material and a solid wall are detectable. For this reason sandwich samples [(4, left) in Fig. 2] are investigated using a steady-state measuring procedure (plate method). From a series connection of the different thermal resistances the unknown contact resistance is computable if the single resistances of the metallic foam (from hot-disk-measurement) and from the used sandwich plates (from tables) are known.

If a cellular material is used to improve heat transfer between a fluid and the surface of the PCM capsule in addition **pressure loss and heat transfer coefficients** have to be determined. For this purpose a well-defined flow is generated, so that the measuring results can be transformed into dimensionless numbers. Figure 2 shows sandwich metal foam samples (4, left) which are implemented in a specially designed flow channel (4, right) where a gas is flowing through the sample [adjusted by mass flow controllers (3)]. Pressure losses are directly, heat transfer coefficients are indirectly measurable from an energy balance.

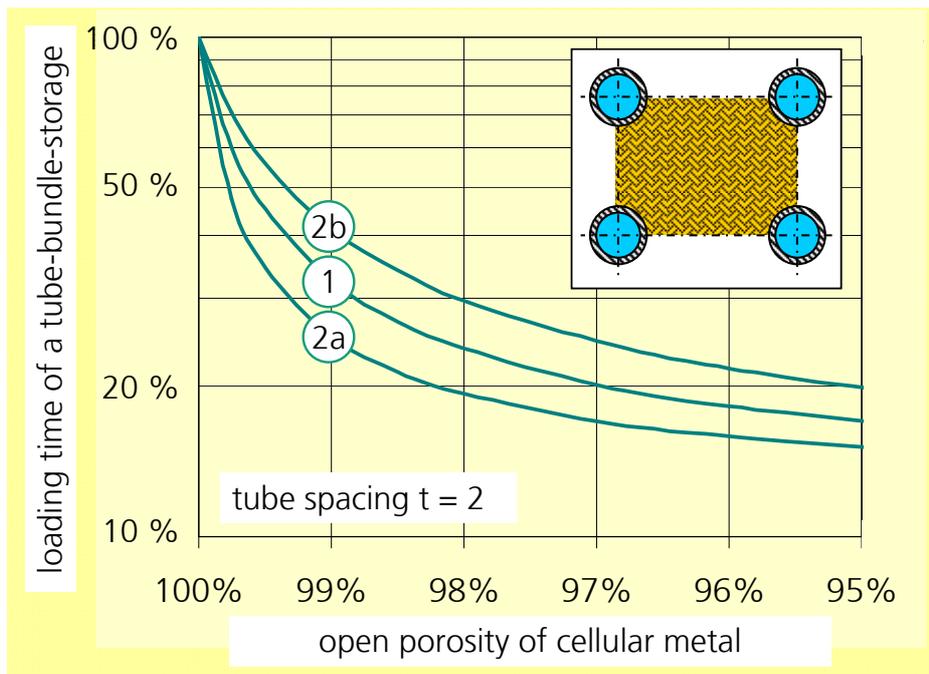
Not only gas flows are possible, also liquids can be used with variable, reproducible volume flow rates and temperature levels. In this way – due to a variation of the strongly temperature dependent dynamic viscosity – variable flow conditions are generated.

## OPTIMISING RESULTS

The target of any optimisation of thermal storages is to adjust the dynamics of loading and re-loading to the requirements of the power engineering system with a similar maximisation of the volumetric storage density. Using cellular metals and metal-matrix-composites, respectively, tailored properties of heat storages and heat buffers are obtainable.



**Figure 3** Effective heat conductivity of a metal-PCM-composite related to those of the pure PCM depending on the porosity of the cellular material

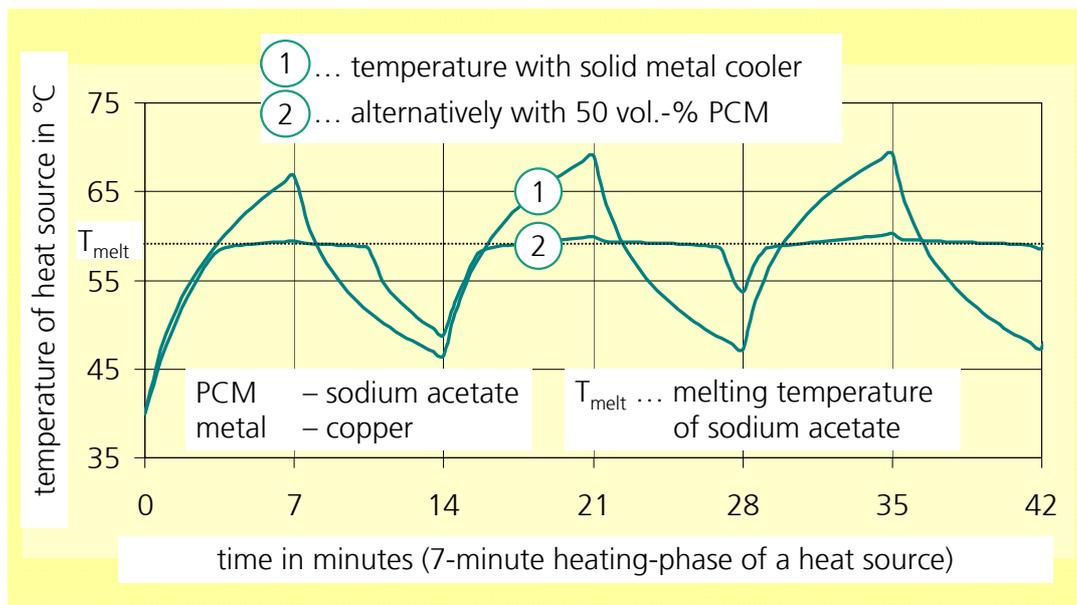


**Figure 4** Decrease of loading time of a thermal rod-bundle-storage due to the higher effective heat conductivity as plotted in Figure 3

Figures 3 and 4 show the effect of inserting a metallic structure in a PCM on the increase of the **effective heat conductivity** and the resulting acceleration of loading and re-loading of a thermal storage. The calculations presented in Fig. 3 are based on a thermal resistance model including the superposition of a parallel and a series connection weighted by factors which depend on the cellular structure. These constants are taken partially from the literature and partially from own measurements.

The plots show that the effective heat conductivity is significantly increased to a 70-times higher value compared to a pure PCM [0.2 ... 0.5 W/(mK)] even in the case of porosities above 90 % (and so a loss in storage capacity lower than 10 %). The effectiveness of a metallic foam is in the range between two different applications of fiber structures. If the major fiber direction is parallel to the heat flux (2a) this structure is more effective compared to foams, otherwise [fiber direction normal to heat flux, (2b)] its effectiveness is lower (anisotropic heat conductivity).

Figure 4 presents results of calculations with respect to the total time required for a complete phase change (loading time) exemplarily for a special type of thermal storage geometry, where the heat transfer medium (water-glycol-mixture) flows inside of a tube bundle and the PCM including the metal matrix is positioned in the outer region. These calculations are executed analytically (STEFAN problem) with some simplifications. It is clearly visible that the loading time can be decreased to 20 % and lower compared to a pure PCM whereas the storage capacity is nearly constant (porosity higher than 95 %, numbering of graphs see Figure 3).



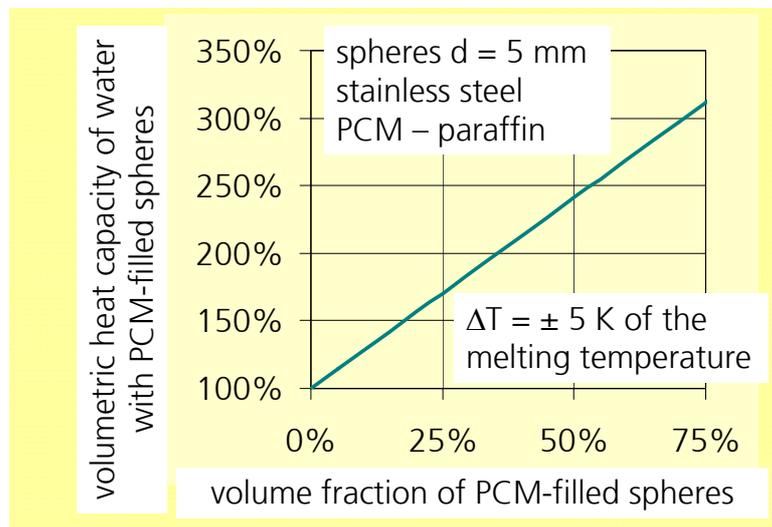
**Figure 5 Time depending surface temperature of a heat source with cyclic load (7-minute-cycle) with a cooling element (heat sink) made of solid metal and a metal-PCM-composite, respectively**

Results of an optimisation of a **heat buffer** are presented in Figure 5. The special application is to cool a power electronic device emitting a constant cyclic heat flux with a 7-minutes-interval. Cooling is realised by means of a metallic cooler with a continuous air flow at its surface (forced convection). Due to the cyclic heat load boundary condition in the heat source region together with a constant air cooling the resulting temperature distribution looks like a "saw tooth" (1).

The maximum temperature can be significantly decreased if in the heat source region a metal-PCM-composite is inserted. In this special application a copper-sodium-acetat-composite is used with a porosity of 50 % (melting temperature of the PCM 59 °C). The effective heat conductivity of this composite is still 25 % of the pure copper [approximately 100 W/(mK)]. By the way a

very high dynamics of loading and re-loading is ensured. The effect of the PCM is clearly seen in the temperature curve (2) by means of the temperature plateau at melting temperature level.

Designing such a cooling application it is definitely necessary to protect a permanent melting of the PCM. In this case the maximum heat source temperature would increase to values above those of a solid cooler because of the lower effective heat conductivity and the very low sensible heat capacity of a molten PCM.



**Figure 6 Increase of volumetric heat capacity of a fluid due to the addition of metallic hollow spheres filled with PCM**

As last example Figure 6 shows the increase of **volumetric heat capacity** of a liquid heat transfer medium by means of the addition of varying volume fractions of PCM-filled metallic hollow spheres (diameter 5 mm, wall thickness 100  $\mu\text{m}$ ). With a volume fraction of 50 % an increase of 2.5 times the pure liquid value is visible. These calculations include the sensible heat capacity (single phase) as well as the latent heat (phase change or melting enthalpy) in a temperature range of  $\pm 5$  K related to the melting temperature. For any storage operating with a lower temperature difference the increase will be more significant due to the changing ratio of latent and sensible heat, respectively.

Metallic hollow spheres filled with PCM are also qualified for the use in building materials (concrete) to improve the thermal capacity of walls designed especially in light-weight construction.