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High-performance thermal capacitors made by explosion forming

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ABSTRACT

This paper addresses the thermal testing of UniPore–paraffin composites for use as thermal capacitors. UniPore is a relatively new porous material with unidirectional pores formed by the explosive fusion of multiple thin copper pipes filled with paraffin. The current study investigates the suitability of this composite for transient thermal energy storage. The application demands both high thermal diffusivity and a large specific energy storage capacity. These requirements are met by the highly conductive copper and the phase change material paraffin, respectively. Combined experimental and numerical analyses are conducted towards the determination of temperature stabilization performance. Furthermore, key geometric criteria for the design of optimum UniPore structures as thermal capacitors are identified.

1. Introduction

Thermal capacitors take an essential role in temperature control, waste energy usage and power intermittency compensation. Their function is the rapid storage and discharge of thermal energy. For temperature control, thermal capacitors are thermally linked to a fluctuating heat source, e.g. a battery in an electric car. Appropriate design allows absorption of thermal energy at the optimum operation temperature of the component. This can be achieved by using a suitable phase change material (PCM) whose phase transition temperature coincides with the targeted temperature. As a result overheating of components is avoided and temperatures are stabilized within the optimum operational range [1]. Another important example for temperature stabilization is climate control in buildings for the compensation of daily and/or seasonal temperature fluctuation [2]. Furthermore, thermal capacitors allow the storage and subsequent use of thermal energy that would be otherwise lost (waste energy) [3]. Finally, in concentrated solar power generation thermal capacitors can be used to attenuate power intermittencies due to cloud coverage [4].

Thermal capacitors have two main requirements (*i*) rapid thermal energy transfer and (*ii*) large specific energy storage capacity. Condition (*i*) arises from the need of storing and discharging energy. Depending on the application (e.g. concentrated solar power generation) high rates of energy transfer are required. Requirement (*ii*) comes primarily from mobile applications (e.g. temperature control in car batteries) where weight and volume are limited and thus light and compact capacitors are needed.

Due to these unique requirements, thermal capacitors are usually composites containing a conductive phase for energy transfer and a phase change material for energy storage. One approach is the use of highly conducting fins that protrude into the PCM in order to increase contact area and energy transfer [5]. The surface area for energy transfer into the PCM can be further increased by using a cellular structure with interconnected porosity. Wang et al. investigated carbonaceous materials as thermally conducting scaffolds that distribute and transfer thermal energy into PCMs [6]. An alternative approach is the use of highly conducting metallic foam for overall conductivity enhancement. Copper foam with interconnected porosity (open-cell foam) has shown great potential for the creation of compact PCM heat sink composites [7]. Mesalhy et al. [8] conducted a numerical heat transfer study of PCM – cellular metal composites. Their results indicated that high porosity foams are advantageous for energy storage and heat conduction since they enable convective heat transfer in the melted PCM. However, this conclusion was challenged in a subsequent study by Tian and Zhao [9]. They argued that due to the large flow resistance of the viscous PCM convective heat transfer is a secondary effect and heat transfer occurs predominantly by conduction.

Recently, a new type of cellular structure with uni-directional pores (UniPore structure) has been produced by compressive blast loading. The fabrication and basic microstructural and mechanical properties of UniPore structures are described in [10], while the

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effect of the compressive compaction on the mechanical properties of the UniPore base material is in detail addressed in [11]. The manufacturing procedure consists of following steps: (i) the outer copper pipe is tightly packed with thin-walled inner copper pipes of much smaller diameter, (ii) the inner pipes are filled with paraffin preventing their complete compaction during compressive blast loading, (iii) the structure is placed in the center of an explosive chamber and surrounded with the explosive (the explosive charge is detonated with an electric detonator). The high pressure blast loading causes compaction of the structure and the outer and inner pipes walls are bonded by diffusion (the phenomenon is similar to diffusion welding). The final step is the removal of paraffin by heat treatment. This manufacturing procedure results in production of porous material with parallel unidirectional pores.

The current study addresses UniPore structure filled with paraffin as thermal capacitors. Their extruded geometry maximizes thermal conductivity in pore direction improving thermal charge and discharge rates. The internal porosity allows the addition of phase change materials such as paraffin for latent heat storage.

2. Methodology

2.1. Experiment

Experimental tests have been performed on UniPore–paraffin composite samples. Three cylindrical samples labeled A (1 mm cell wall thickness), B (0.6 mm cell wall thickness) and C (0.4 mm cell wall thickness) with a constant height h = 150.0 mm and average outer diameter d = 27.1 mm have been investigated. The cross sections of these samples are shown in Fig. 1. The selection of the initial pipe diameter and thickness together with the control of the compressive forces during explosive fusion allow the variation of sample porosity. This is reflected in the copper volume fraction Φ_{Cu} of the cross sections ranging from 53.3–77.5%. The internal voids are filled with the phase change material (PCM) paraffin with the corresponding paraffin volume fraction Φ_{Pa}. Since pores are refilled with liquid paraffin and the material contracts upon solidification some residual porosity remains in the PCM. During repeated melting and solidification, these pores tend to accumulate at the upper surface of the samples.

The circular sample surfaces (top and bottom) were polished in order to minimize thermal resistance by removing the oxide layer and creating a plane contact surface. Next, the samples were sealed using copper lids that were pressed against these polished surfaces. The sealing of the sample is necessary to prevent the leakage of liquefied paraffin. Sealed samples were positioned upright on a copper heating plate simulating the heat source (see Fig. 2). In an attempt to decrease thermal contact resistance a thin layer of thermal conducting paste (Omegatherm® 201 silicone paste) was applied between the touching sample lid and heat source. Measurements were conducted inside a vacuum chamber in order to avoid energy loss due to convective heat transfer. Furthermore, reflective radiation shields were used to minimize energy loss by thermal radiation and ceramic stands reduce energy loss due thermal conduction. As a result, the entire system can be considered adiabatic in good approximation.

Prior to each experiment, heat source and sample were cooled to ambient temperature to ensure a uniform initial temperature distribution. Next, the pressure inside the vacuum chamber was decreased below 20 mPa before the electric power input P into the heating element was activated. A heating wire is embedded in the copper heating plate and converts the electric power into a thermal energy flux triggering a temperature increase. Temperature change was monitored using a RTD100 temperature sensor positioned on the heating element. Due to the design of the heating element it exhibits a uniform surface temperature with variations below 1 K. Accordingly, the sensor temperature closely represents the interface temperature between heat source and sample. The temperature was recorded in 1 s time intervals using an OM-DAQ-PRO-5300 (Omega®) data logger. Tests were terminated after the measured temperature exceeded 395 K. For the energy input P = 50 W all tests have been conducted twice in order to test measurement precision. No significant deviation between measurements was observed. Furthermore, the sample orientation was inverted (i.e. the sample was rotated by 180°) and again no visible changes in the measured time–temperature curves were found.

2.2. Simulation

Numerical Finite Element simulations were conducted in order to gain additional insight in the temperature distribution within the composite samples. To this end, cross sections shown in Fig. 1 were segmented, i.e. pixel color information was used to identify the metallic phase (see black color, Fig. 3). The internal voids of the segmented images were filled with paraffin (grey color) and the resulting cross sections were extruded to create the three dimensional models. It should be mentioned here that the cross sections of the tested samples are not completely constant but slightly change with the height of the samples. However, the deviation between real samples and extruded model is small. This can be demonstrated by calculating the masses of the model structures and comparing them with the measured masses of the samples. The resulting deviations are less than 3.1%.

In the next step, the finite element mesh of the UniPore models was prepared. Due to the extruded geometry of the models it was possible to use exclusively hexagonal finite elements. Special care was taken to ensure that the average aspect ratio of all elements was smaller than two and that the worst aspect ratio was not larger than five. In order to reduce the computational cost of the sim-

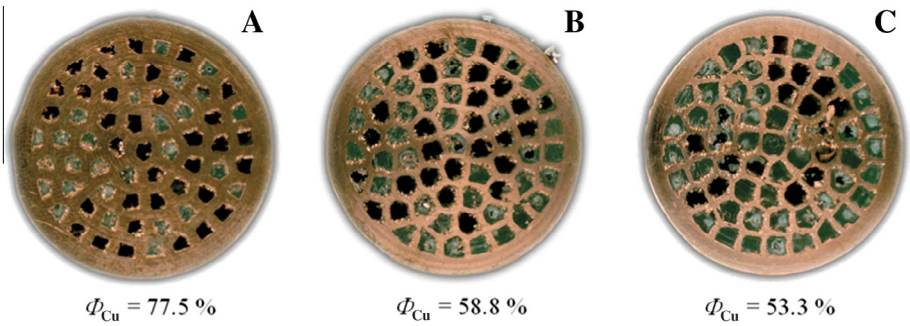

Fig. 1. UniPore–paraffin composite cross sections.