

Metal foam – a material for heat engineering

Porous structures increase the efficiency of heat exchangers and cooling elements



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Metal foams are increasingly developing into materials with diverse uses. While metal foams with closed pores have already become established as rigid and strong lightweight materials, the open-cell variant is suitable for thermal engineering applications. Until now, the material has been rarely used in heat exchangers or coolers because the production is expensive and its application little tested. Researchers at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM in Dresden now want to change this. Together with industry partners, they are further developing the production method, are characterising different metal foams and are testing them in practice.

Metal foams provide an ideal prerequisite for constructing heat exchangers, coolers and convectors. Their porosity of up to 95 per cent makes it easy for gases or liquids to flow through them, whereby the large surface area of the foam together with the good conductivity of the metal enables the transmission of large amounts of heat. Open-cell metal foams can be made with cell widths between 0.3 and 5 mm. However, the thermal and fluid dynamic behaviour of the different metal foams had not been sufficiently researched in the past. This was, together with the high production costs, the biggest hurdle for using the material in power engineering.

m.pore GmbH is one of the few companies capable of producing open-pore metal foams in a precision casting process: open-cell polyurethane foams that are available in different pore sizes are used as the model for the casting. The size of the pores and the thickness of the webs between the pores dictate the subsequent properties of the metal foam. In a first step, the technicians stabilise the

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thin webs with wax and bring them to the desired thickness. They then cast the plastic with a liquid ceramic suspension. Its high water content enables it to penetrate into the fine pores and fill them. It dries and solidifies at a temperature of 120 °C. A further increase in temperature to 600 °C decomposes the shaping plastic and cures the resulting refractory mould. The still hot mould can now be filled with any castable metal alloy. Aluminium alloy is used for most applications. After cooling, the speciality ceramic decomposes and can be washed out.

The researchers have optimised each individual process step for a new business location. Partial automation has enabled them to more than double the furnace throughput and reduce the specific energy consumption. In the future it is intended to treat and reuse both the water and the ceramic. The manufacturing process is used to produce foam metal sheets 450 x 250 x 40 millimetres in size. Their inner surface is about the size of a football field.

Powder metallurgical process

If metal foams are required with very small cell diameters, the precision casting process is pushed to its limits. The metal no longer flows completely into the cavities when the pore diameters are less than about one millimetre in size. However, scientists at Fraunhofer IFAM in Dresden can create such delicate structures using a powder metallurgy manufacturing technology that was developed several years ago. They also use wax-stabilised PU foam as the shaping model. They coat this with a metal powder-binder suspension. They then decompose the resin and the binder by applying high temperatures. What remains is a powder metal skeleton that is sintered to form a solid structure at about 80 % of the melting temperature of the metal alloy used. The trick is to avoid cracking and pore defects. Researchers have improved the method with new powders and binders. In particular, they have recently succeeded in producing small-cell copper foams.

Systematically measuring metal foams

The pore size, web thickness and shape as well as the choice of metal alloy substantially determine the thermal and fluidic properties of metal foams. However, it has not yet been possible to precisely predict these properties using mathematical models. The scientists have therefore developed different test rigs to systematically measure the effective thermal conductivity of the metal foams and metal fibre samples, the heat transfer to a gas flow and the pressure loss generated by the metal structures. They have summarised the measurement results in a database. This also serves as a basis for improving the modelling of metal foams mathematically.

Can metal foams and metal fibres also exploit their physical advantages relative to conventional coolers, heat exchangers or convectors in practice? Experimental investigations conducted on various technical systems have tried to answer this question.

Increasing the performance of latent heat storage systems

Latent heat storage systems use the high melting heat of paraffins, salt hydrates, salts or water. The storage mass solidifies when the heat is removed and forms an

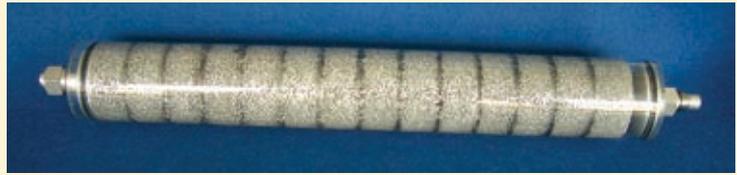


Fig. 1 Latent heat storage device with aluminium foam-paraffin composite



Fig. 2 In addition to metal foams, selected fibrous structures were also produced as sandwich samples for the heat transfer measurements

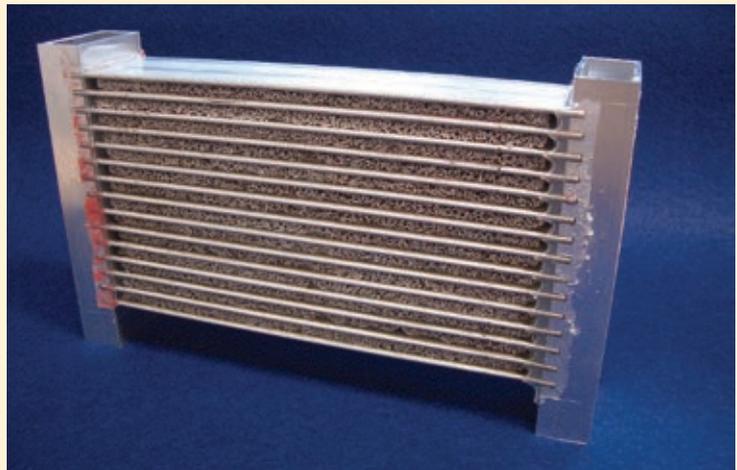


Fig. 3 Metal foam replaces the lamella structure in a model cooler.

insulating layer that hinders the further extraction of heat. The effective thermal conductivity can be significantly increased when the storage material is embedded in a thermally conductive metal foam matrix. Researchers have tested this using a paraffin storage system with a melting temperature of 42 °C.

They installed aluminium foam slices in the cylindrical latent heat storage system, which are connected with bonded joints to the heat exchanger tube in the cylinder axis. The aluminium foam achieves with 10 pores per inch (ppi) a porosity of 89.5 % and reduces the effective thermal mass by only about 10 %. With a length of 40 cm and a diameter of 12 cm, the cylinder absorbs 550 grams of paraffin. This corresponds to a latent storage capacity of about 96 kJ. The module can be combined to form any amount of tube bundles, so that the measuring results can also be transferred to larger storage systems.

The aluminium's excellent conductivity enables the storage system to achieve an average discharge capacity of 140 W and a charging capacity of 175 W. The scientists are convinced that they can further increase the



Metal fibre structures

Metal fibres sintered to form mouldings are superior to metal foams in some application areas. Fraunhofer IFAM Dresden is producing short fibres between 5 and 50 mm in length and 50 to 250 μm thick by using melt extraction. Here a water-cooled copper wheel rotates in a melt bath containing a liquid metal alloy as the melt. The melt adheres to the wheel and is drawn out into a thread as it rotates. The resulting fibres separate from the wheel through shrinkage and centrifugal forces. Almost all metal alloys can be processed in this way to form fibres. Shaped and sintered in a bulk process, this results in tailor-made discs, rings or plates. The highly porous mouldings tolerate high temperatures such as occur in catalytic converters for cars, acoustic and thermal insulation used for machines or exhaust filters for industry. Whereas with metal foams the heat conduction and flow pressure loss are independent of the direction, with fibrous structures they are determined by the position of the fibres. This anisotropy can be used in a targeted manner.

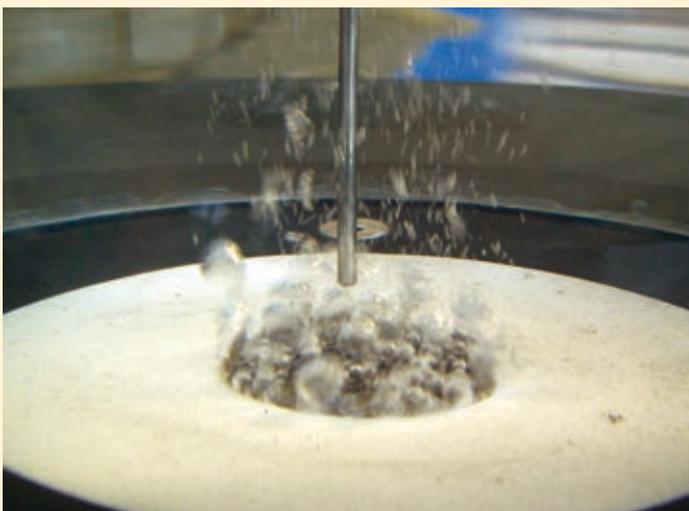


Fig. 4 Investigations on the high-performance evaporator:
top: nucleate boiling, below: supercooled boiling

heat output with metal fibre structures. For the same porosity, the material has a higher thermal conductivity in the fibre direction and a significantly larger contact surface to the heat transfer channels. In addition, the material is more mechanically stable and can be processed more accurately.

Car radiators – heat output versus pressure loss

Despite their compact design, car radiators feed the engine waste heat with a high output to the outside air. This is made possible by a lamella structure through which the cooling air flows. It has proven to be a good compromise between achieving a high heat transfer and a low pressure loss. Laboratory tests were intended to show whether the thermal power can be increased again when metal foams are used instead of the lamellas. However, a test radiator with a 30 ppi aluminium foam structure has so far been unable to provide a clear answer to this question. Although it achieved a higher heat output than a lamella radiator, the pressure losses also increased. Consequently, a higher fan output would also have to be accepted.

Both effects are even stronger when fibrous structures are used in the conventional cooler geometry. The intensive heat transfer already heats the air after a short distance. The rest of the run length hardly contributes to the heat dissipation but increases the pressure loss. This is where the researchers see considerable potential for optimisation by harmonising the fibre, flow and heat flow directions.

High-performance evaporators

High-performance evaporators solve cooling problems where simple refrigeration units reach their performance limits. They bring coolants to boiling point and thus discharge heat via the steam. The efficiency with which they work depends decisively on the evaporator surface. A large surface can be produced with aluminium foam. Another advantage are the sharp-edged foam webs that act as bubble nucleates. In several measurement series, the researchers showed that the boiling process with metal foam boiling surfaces occurs with significantly lower excess temperatures for the evaporator surface than with an unstructured surface, which means that significantly higher evaporation rates are possible. Optimising the pore size, web thickness and foam height prevents a vapour cushion forming in the foam layer that hinders the steam discharge. Since evaporation processes are considerably important in power generation, refrigeration and process engineering, the researchers are continuing these investigations in follow-up projects.



Easier and safer

When considerable stiffness is required in mechanical and vehicle engineering, but at the same time every gram counts, one option is to use aluminium foams with closed pores. One way to produce them is to blow gas into the molten metal and skim off the foam produced. More common, however, is the powder metallurgy process. Here, manufacturers mix metal powder with a blowing agent. Pressed into shape and heated above the melting point, the molten metal rises like yeast dough. This makes it possible to fill hollow bodies with foam and thereby also produce complex shapes. Depending on the porosity, metal foams weigh only a fifth of the equivalent solid material. With a density of 0.3 to 0.8 grams per cubic centimetre, they even float on water, but are nevertheless rigid and dimensionally stable. The pore structure reduces the thermal and electrical conductivity. Vibrations and noises are greatly attenuated. Used as crash elements or bumpers, the foam deforms more evenly than solid metals when subject to external forces, whereby it also absorbs energy. The material can be easily processed mechanically and is not flammable. Lightweight components can also help to increase the range and reduce the energy requirements of electric vehicles. The Fraunhofer IWU, IFAM and WKI institutes are developing and testing the entire process chain for lightweight structures. In the „FunTrog“ project, they are developing, for example, a multifunctional battery container for electric vehicles. This is twenty per cent lighter than the reference assembly made of steel and provides a more rigid structure. The lower shell of the trough, which has a sandwich structure, consists of an aluminium foam core encased by a cover plate made of metal and a bottom plate made of glass fibre-reinforced thermoplastic.

Network for Cellular Metallic Materials

Scientific institutions and manufacturers have joined together in the Cellular Metallic Materials Network in order to bundle the expertise of the members. The network is managed by Fraunhofer IWU in Chemnitz. In particular the network intends to initiate and conduct research projects in which the materials are further developed and deployed for existing and new applications.

Project participants

- » **Systematic characterisation of open-cell metal structures, project management:**
Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, institute section in Dresden, Prof. Dr.-Ing. Jens Meinert, jens.meinert@ifam-dd.fraunhofer.de
- » **Development of prototype components for heat transfer and heat storage:**
WätaS Wärmetauscher Sachsen GmbH, Volker Schubert
- » **Casting-based manufacturing of open-cell metal foams:** m.pore GmbH, Mike Bücheler

Links and literature (in German)

- » www.ifam.fraunhofer.de » www.iwu.fraunhofer.de
- » Synowzik, S.; Meinert, J.; Andersen, O. u. a.: Charakterisierung offenzelliger Metalle für energieeffiziente Technologien COMET. Teilvorhaben A-C. Schlussbericht. FKZ 03ET1023A-C. Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM), Dresden (Hrsg.). Juli 2015. 96 S.

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