Systematic thermal and flow characterisation of open cellular structures

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Introduction

In general cellular materials are divided in open and closed structures. Typical representatives of so-called open cellular materials are foam (1), fiber (2) and wire structures (3) as shown and marked in Figure 1. Its main characteristics are the possibility of a flow passing through the structure and the large inner volumetric surface. Consequential a large number of applications in the field of power engineering result. This includes the use in heat exchangers especially with gaseous fluids, in thermal energy storage devices a heat conducting matrix, as self-supporting high-temperature heat insulation – possibly combined with acoustic damping – and in catalysts or filters as primary structure, respectively.

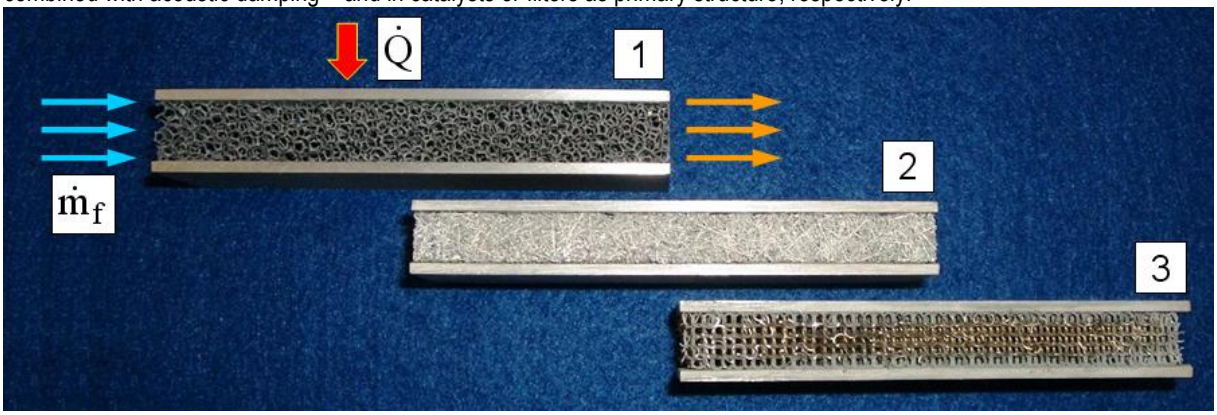

Figure 1: Open cellular metals prepared as sandwich structures

Open cellular foams and fiber structures developed and investigated at Fraunhofer IFAM Dresden are manufactured from metals (stainless steel, aluminium, copper) using powder metallurgical routes [1-2]. Metallic wire structures are manufactured and provided by Kieselstein GmbH in Chemnitz.

To optimise flow, temperature distribution and heat transfer in the above mentioned technical applications detailed information about the thermal and flow behaviour are needed: effective heat conductivity, the flow resistance (pressure loss, permeability) and heat transfer characteristics. Because of the irregular geometry especially of foam and fiber structures the characterisation has to be executed experimentally. This paper gives a short survey on the used experimental setup as well as the data evaluation procedure and shows selected measuring results.

Experimental setup

Pressure loss

To measure the pressure loss of a gas or liquid flow in a cellular metal special samples have to be prepared and implemented in a flow channel. At Fraunhofer IFAM Dresden two test facilities were developed: a cylindric and a prismatic one. The main advantage of the cylindric channel is a simple sample sealing, whereas the prismatic channel is qualified for heat transfer measurements (see below).

The cylinder channel (scheme in Figure 2) has an inner diameter of 20 mm and a length of 400 mm to homogenise flow conditions. Cellular metal samples (Ø 20 mm) of variable thickness are implemented in an aluminium ring (see Figure) to avoid any enlargement of the cross section. The upstream pressure p_{up}, the pressure difference along the sample Δp and the barometric pressure are measured by means of piezo-electric pressure transducers. A circular manifold is used at each position to get an averaged static pressure value.

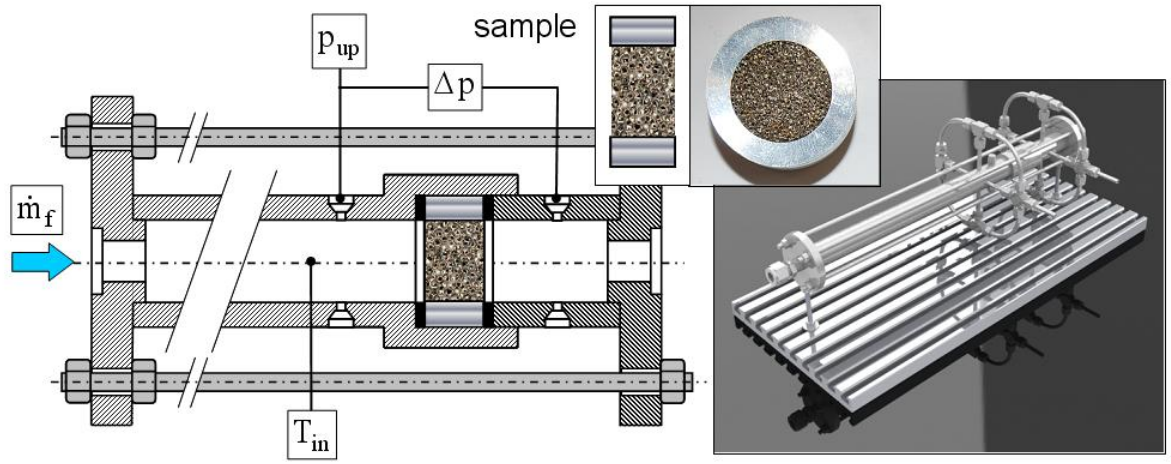

Figure 2: Cylindric flow channel for pressure loss measurement

The fluid presently is provided from a compressed air system (other gases possible), adjusted by mass flow controllers (mass flow $\dot{m}_f$) and – especially to modify the viscosity – heated up using an electric heater. So the inlet temperature T_{in} is variable up to 650 °C at flow rates lower than 250 standard litres per minute. A defined water flow also can be generated using a Coriolis flow meter (max. 5 l/min) and tempered between 5 °C $\leq T_{in} \leq$ 90 °C. From the measured inlet flow condition the superficial velocity is determined as base for a later data evaluation (pressure loss versus Reynolds number).

Heat transfer

For any application of open cellular metals in heat exchangers or catalysts the heat transfer characteristics between the fluid and the solid structure is very important. The local heat flux between fluid and structure depends first on the wetted inner surface of the volume element, second the heat transfer coefficient and third the local temperature difference. The main advantages cellular aluminium or copper structures result from a combination of a very large inner surface per unit volume and a high heat transfer coefficient due to turbulent transport phenomena as a consequence of the irregular and edged structure. Normally the measurement of local heat transfer coefficients will not be possible so that the results are plotted integrally related to the wall surface (contact surface of cellular structure and wall).

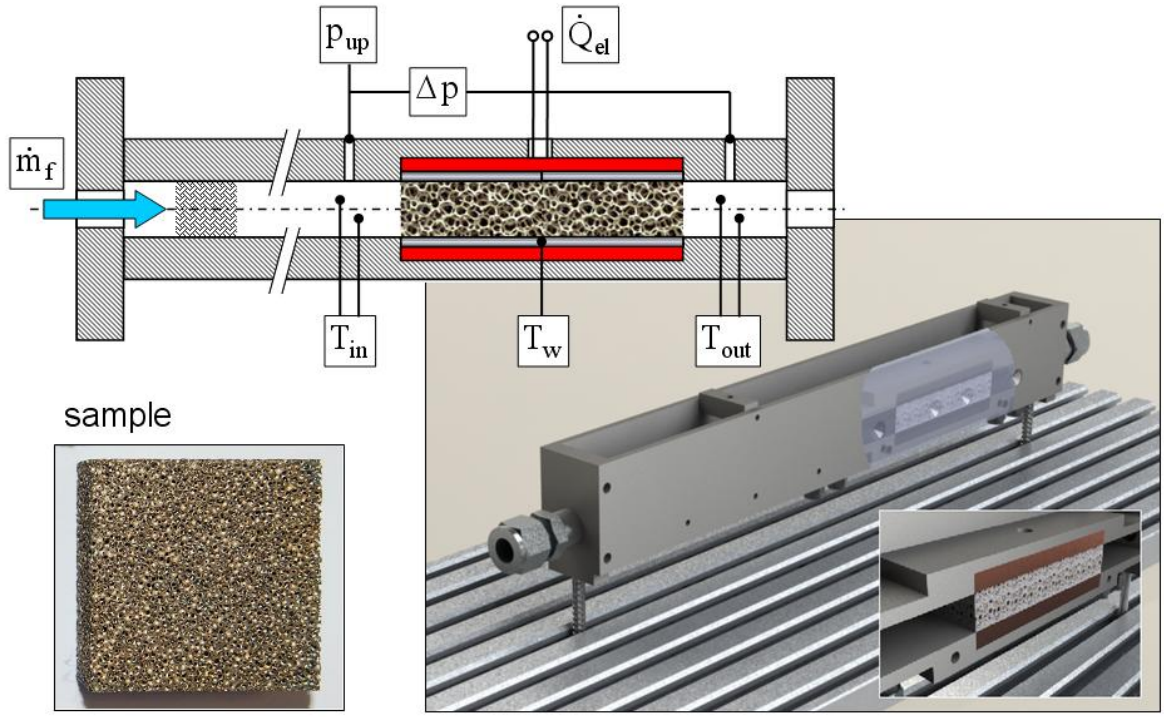

Figure 3: Prismatic channel for flow and heat transfer characterisation

Figure 3 shows the scheme of a prismatic flow channel (total length 400 mm) which is qualified for flow as well as heat transfer investigations. Prismatic samples of cellular metals (fixed width 30 mm, flexible height, heated length 90 mm) are

positioned in this channel between electrically heated copper plates on the bottom and top side. Its prismatic geometry allows the variation of sample position to investigate anisotropic flow effects. Different fluids (air, water) are provided from the same peripheral equipment as described above.
Besides the measurement of pressure differences the heat transfer coefficient is determined from an energy balance. For this reason the inlet (T_{in}) and outlet fluid temperature (T_{out}) as well as the wall temperature (T_w) of the heated section are measured at multiple positions and averaged ($\overline{T}$). Assuming nearly adiabatic side walls the energy balance can be written equalising the enthalpy change of the fluid and the convective heat flux:

$$\dot{Q} = \dot{m}_f \, c_{pf} \, (\overline{T}_{out} - \overline{T}_{in}) = \alpha \cdot A_w \, \Delta T_{ht} \quad \text{with} \quad \Delta T_{ht} = \frac{\overline{T}_{out} - \overline{T}_{in}}{\ln \dfrac{\overline{T}_w - \overline{T}_{in}}{\overline{T}_w - \overline{T}_{out}}} . \qquad (1)$$

As heat transferring surface A_w the area of the heated copper plates is used and by the way an integral heat transfer coefficient α is resulting. Consequently it has to be considered that measuring results of different samples only can be compared in the case of a similar sample height. By means of neglecting the temperature distribution in the cellular structure the heat transfer results become easier to handle but less general.

Heat conductivity

The effective heat conductivity of cellular metals represents an important property with respect to all applications in the field of thermal insulation and heat conducting matrices in low conductive materials (e. g. phase change materials). Two test facilities with a special qualification for heat conductivity measurements of cellular structures are described.
The first one is a steady-state plate method (top scheme in Figure 4). The cellular sample (4) is positioned together with a reference material (3) between an electric heating (1) and a cooling plate (5) with an outer insulation (Styrofoam spheres). Copper plates equipped with thermocouples and heat conducting foils on both surfaces (2) are used to determine the temperatures. Samples of variable height with several ground areas [30 x 30, 100 x 30, Ø 30 or 50 x 50 (all in mm)] can be used. Adjusting the mid-level at room temperature heat losses are minimised. Comparing ΔT_{ref} with ΔT_{sam} and considering all additional thermal resistances the unknown sample heat conductivity is calculated from Fourier's Law.

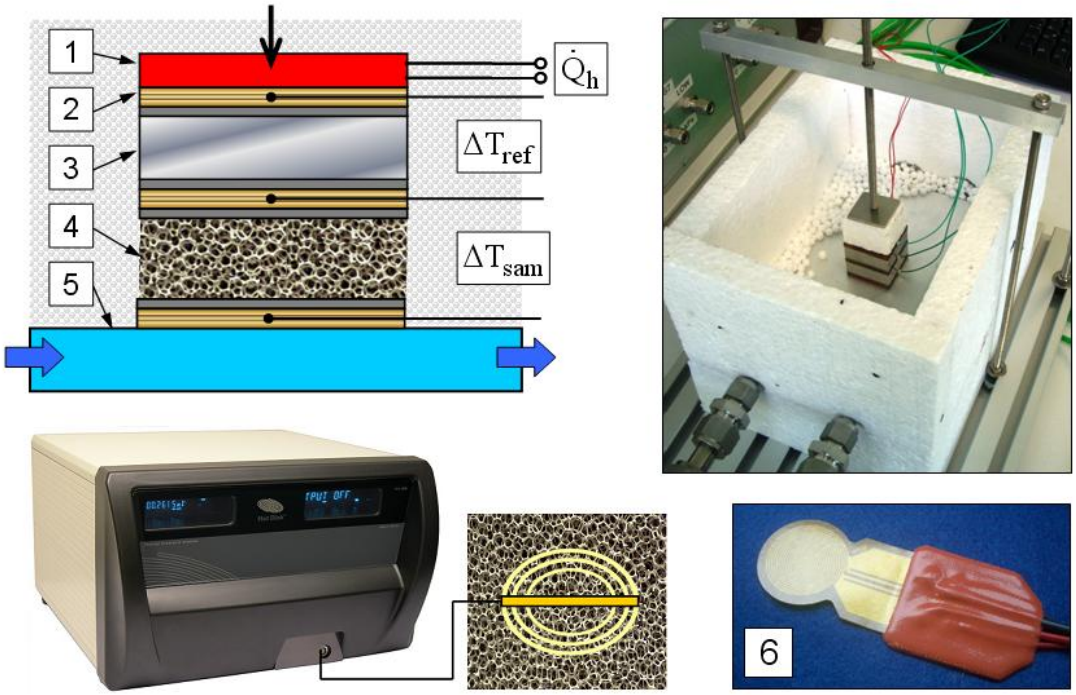

Figure 4: Heat conductivity measurement

A second measuring procedure is the so-called Hot-Disk method (bottom in Figure 4). A flat sensor – a combination of electric heater and resistance thermometer (6) – is placed between two identical samples. Different sensor diameters between 4 and 60 mm are available – its size has to be adapted to the cellular structure (integrating behaviour). After a short heating sequence the time-dependent sensor temperature is plotted. Solving Fourier's differential equation describing the transient temperature distribution the unknown heat conductivity of the sensor surroundings (= sample) is determined [3].

An essential fact affecting the accuracy of the heat conductivity measurement is the contacting between sample and sensor. For this reason thin, heat conducting foils are used to balance irregularities in thickness in the plate test facility. Because this is not practicable with the Hot-Disk method this measuring procedure is very responsive in this regard.

Typical sample matrix and selected results

To quantify the influence of several parameters such as pore size and structure geometry, porosity (or effective or relative density), bulk material and manufacturing route a wide selection of samples has to be investigated. In the following some selected results of flow and heat conductivity characterisation should be presented for a foam sample matrix.

structure geometry	open foam
bulk material	stainless steel 316L
manufacturing route	powder-metallurgical based on Polyurethan-foam
pore sizes [ppi]	20, 30, 45, 60 and 80 (right side in Figure 5)
effective density [g/cm³]	0.6, 0.7, 0.8, 0.9 and 1.0 (corresponding porosities 0.85 – 0.95)
sample geometry [mm]	Ø 20 x 15 (1), Ø 30 x 15 (2), 30 x 30 x 15 (3) (left in Figure 5)

By the way totally 125 samples were prepared and investigated (5 pore sizes x 5 densities x 5 geometries). Sample type (1) is used in the cylindric channel, type (3) in the prismatic channel and types (2) and (3) additionally used for heat conduction measurements.

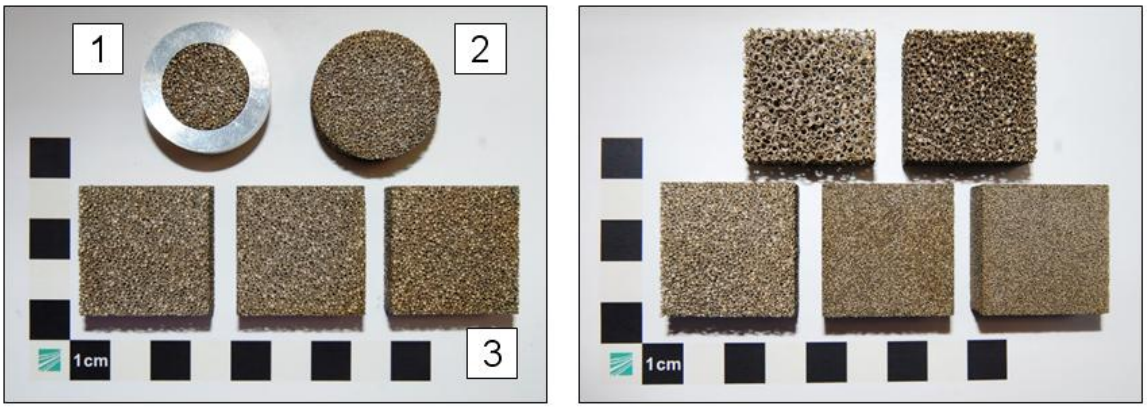

Figure 5: Metal foam sample matrix – variable geometries and pore sizes

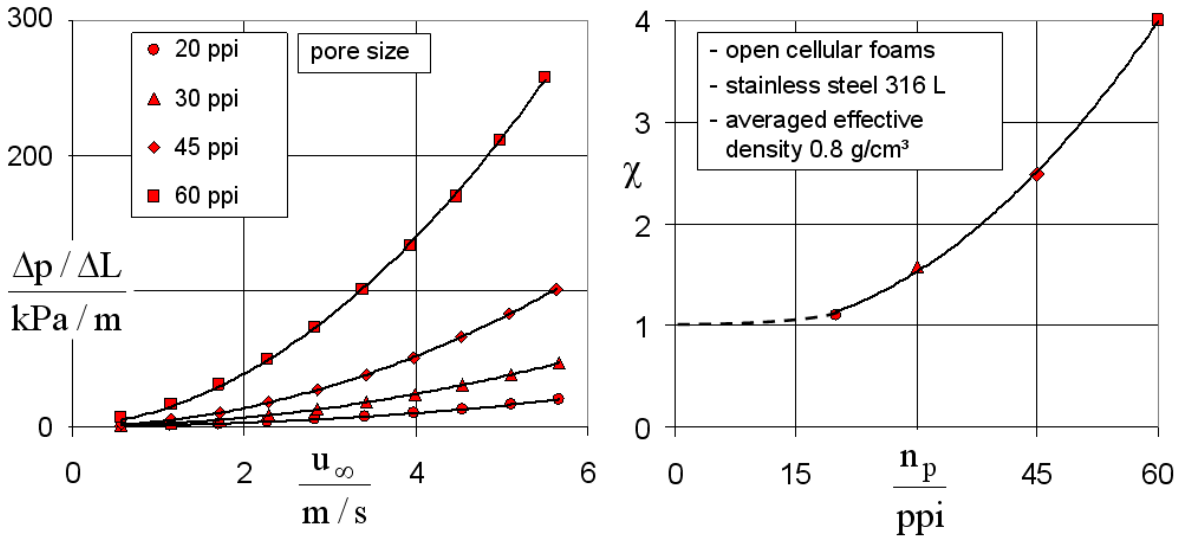

Figure 6: Pressure losses and tortuosity for a gas flow through metal foams

The left plot in Figure 6 shows typical results for a gas flow through a foam structure plotted as pressure loss per unit length versus superficial velocity u_∞. Pressure loss increases with decreasing pore size at a nearly constant effective density. The parabolic distribution illustrates the dominance of turbulence effects in foams.

An important mathematical model to describe the flow in porous structures is the channel model which finally results in the so-called Ergun equation [4, 5]. Eq. (2) represents a modification introducing the volumetric inner surface φ (determined adjusting the measured porosity ε and pore size to a geometrical tetrakaidecahedron cell model [6]) and the tortuosity χ [7]

$$\frac{\Delta p}{\Delta L} = \left(2\,\frac{\varphi\,\eta\,u_\infty}{\varepsilon^3} + 0.1392\,\frac{\varphi\,\rho\,u_\infty^2}{\varepsilon^3} \right) \cdot \chi \qquad (2)$$

(ρ - density, η - viscosity). Adapting Eq. (2) to the measurements by varying the tortuosity (least square method) a value of χ can be determined for each sample and plotted versus pore size n_p (right in Figure 6). The fitting line tends to χ = 1 (straight flow) for very large cells.

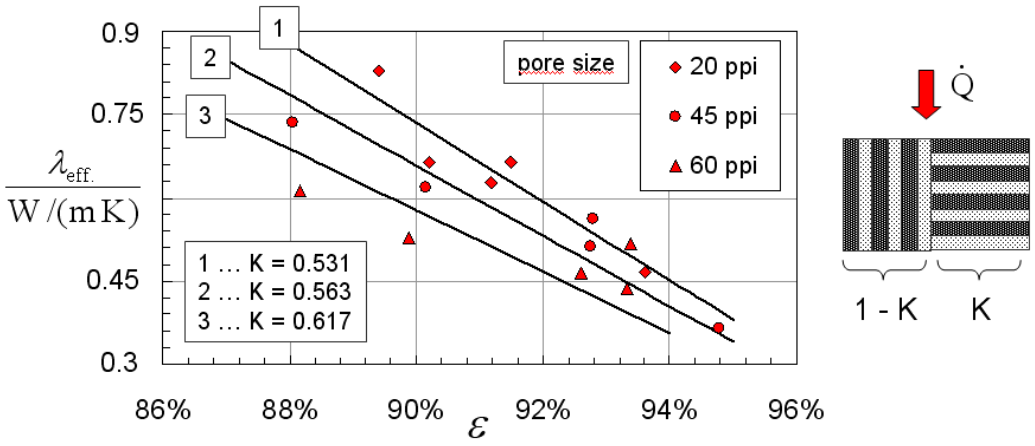

Figure 7: Effective heat conductivity of stainless steel foams (plate test facility)

The effective heat conductivity λ_{eff} of stainless steel foams was measured using the plate method and is plotted versus porosity ε in Figure 7. With increasing porosity the heat conductivity decreases as expected. The lines correspond to a coupled thermal resistance model based on the heat conductivities of the bulk material λ_b and the gas λ_g [8]

$$\lambda_{eff} = (1-K)\cdot[\varepsilon\,\lambda_g + (1-\varepsilon)\cdot\lambda_b] + \frac{K}{\frac{\varepsilon}{\lambda_g} + \frac{1-\varepsilon}{\lambda_b}} \qquad (3)$$

A factor K weights the fraction of series and parallel connection [9] as shown in Figure 7 and is adapted to the measuring results.

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