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Periodic open cellular structures with ideal cubic cell geometry: Effect of porosity and cell orientation on pressure drop behavior

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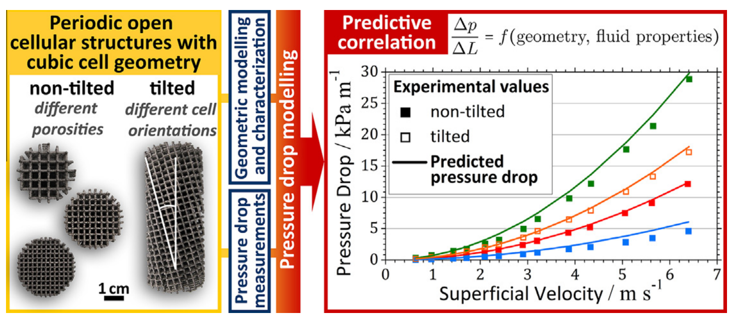
HIGHLIGHTS

- Periodic open cellular structures with cubic cell geometry were manufactured.
- The investigated structures differ in their porosity and tortuosity values.
- The pressure drop of the different samples was determined experimentally.
- A model to calculate the specific surface area is presented and validated.
- A fully predictive correlation to calculate the pressure drop is derived.

GRAPHICAL ABSTRACT



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ABSTRACT

Periodic open cellular structures (POCS) with ideal cubic cell geometry (icPOCS) were manufactured via the selective electron beam melting technique (SEBM). Depending on the cell dimensions (cell length, strut diameter) and cell orientation in respect to the main axis of the cylindrical structures, the icPOCS investigated in this work exhibit different porosities and/or tortuosities. The structures were characterized with respect to their morphological and geometrical parameters such as strut and cell dimension, specific surface area, and porosity using different techniques (e.g., micro-computed tomography and helium pycnometry). Additionally, a model for the calculation of the specific surface area is presented which takes surface roughness into account. The model enables the determination of the specific surface area on the basis of only two geometrical parameters, i.e., the strut diameter and the cell length, which are both easy to determine for such highly regular open cellular structures. The pressure drop of the icPOCS was measured with air as working fluid. A correlation allowing for the prediction of the pressure drop of icPOCS was developed based on the Ergun equation in its basic form. The presented correlation reflects the porosity and cell orientation and is solely based on the geometric properties of the structures. As the correlation does not rely on the use of empirical fitting parameters it is fully predictive.

1. Introduction

For technical applications, the active material which is originally available in fine powder form has to be shaped and coated on a support in a suitable manner. The most common option is to use spherical or cylindrical carrier particles which can then be used in classical randomly packed fixed beds for catalytic and/or adsorptive processes, e.g. in the chemical and petrochemical industries. Another possibility is the coating of planar carriers such as, e.g., the walls of a channel. This leads to the concept of monolithic honeycombs which consist of a parallel arrangement of a multitude of such channels. Monolithic honeycomb reactors are state-of-the-art in exhaust gas treatment processes and are in general an interesting option for applications where very high gas flow rates have to be realized [e.g. 1–3].

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Nomenclature

Abbreviations

(ic)POCS	periodic open cellular structure (with ideal cubic cell geomentry)
CPI	cells per inch
RUC	representative unit cell; i: based on ideal RUC geometry, sr: including surface roughness, lit: based on literature
SEBM	selective electron beam melting
SSA	specific surface area

Symbols

a_V	total volume based specific surface area $a_V = A_{solid} \cdot V_{bulk}^{-1}$ (m^{-1})
$a_{V\text{-solid}}$	solid volume based specific surface area $a_{V,solid} = A_{solid} \cdot V_{solid}^{-1}$ (m^{-1})
a, b	fitting parameter (kPa m^{-1})
a_1, b_1	fitting parameter (kPa s^2 m^{-3})
a_2, b_2	fitting parameter (kPa s m^{-2})
A	surface area (m^2)
d	diameter (m)
d_p	particle diameter (m)
$d_{p,eq}$	equivalent d_p of a sphere $d_{p,eq} = 6 \cdot (1 - \varepsilon_V) \cdot a_V^{-1}$ (m)
f, f_{mod}	(modified) friction factor (–)
F	conversion factor (–)
K_N	constant for node volume calculation (–)
l, L	length, total length (m)
N	number (–)
p	pressure (Pa)
$\mathrm{Re}_{p(,mod)}$	(modified) particle Reynolds number $\mathrm{Re}_p = u_{sf,0} \cdot d_p \cdot \rho_f \cdot \eta_f^{-1}$ $\mathrm{Re}_{p,mod} = \mathrm{Re}_p \cdot (1 - \varepsilon_V)^{-1}$ (–)
u_{sf}	superficial velocity; $u_{sf,0}$: at position 0 → sample inlet (m s^{-1})
V	volume; bulk volume $V_{bulk} = V_{solid} + V_{void}$ (m^3)

Subscripts

A	area based
C	cell
eff	effective
exp	experimentally determined
f	fluid
min	minimum
N	node
S	strut
V	volume based
W	window
x–y	cell orientation (x, y = tilt angle along x-, y-axis)
$\perp$	perpendicular to the main axis

Greek symbols

α, α^*	coefficients for the viscous term (–)
β, β^*	coefficients for the inertial term (–)
$\Delta p \Delta L^{-1}$	pressure gradient: pressure drop per unit length (kPa m^{-1})
ε_A	area related porosity $\varepsilon_A = A_W \cdot A_C^{-1}$ (–)
ε_V	open porosity $\varepsilon_V = 1 - V_{solid} \cdot V_{bulk}^{-1}$ (–)
Φ	specific length ratio $\Phi = l_W \cdot l_C^{-1}$ (–)
η	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
τ	tortuosity (–)

Besides monolithic honeycombs, structured packings and foam-like structures in particular gained a lot of interest as catalyst supports in recent years as they are characterized by some important advantages compared to classical randomly packed beds and/or honeycomb monoliths: (i) Due to the high porosity of such structures the corresponding pressure drop is very low while (ii) at the same time the specific surface area is large, (iii) the heat conductivity [4] and the mechanical strength is enhanced (as a result of the continuous solid fraction), and (iv) radial mixing of the fluid is possible [5]. For these reasons, open cellular foams are promising candidates for a variety of heat- and mass-transfer related applications [e.g. 4,6–14].

The prevailing manufacturing principle of solid open cellular foams is the replication technique. The resulting so-called reticulated foams are of irregular nature and feature always a broad distribution in the characteristic foam dimensions, such as porosity, strut thickness, and window opening size [15,16]. Despite the irregular nature, most attempts reported in literature regarding the structural description and the properties of the irregular reticulated foams are based on simple geometric models such as the *kelvin* cell or a cubic lattice [e.g. 17–21]. However, the irregularities complicate the reliable prediction of properties such as pressure drop and heat transfer, which depend on the interaction of the fluid with the surface.

Nowadays, the selective electron beam melting of metallic powder (SEBM) [22] offers the possibility to highly reproducible manufacture periodic open cellular structures (POCS) with a well-defined, ordered geometry and with desired dimensions. Therefore, such POCS are perfectly suited for systematic studies concerning heat transfer and flow characteristics in open cellular structures. In principle, an infinite number of geometries of the accordant representative unit cells (RUC) of POCS manufactured via SEBM are feasible such as diamond [23] or tetrakaidecahedral [24] (one of the idealized basic geometries which were often used as a model to describe the structure of reticulated foams). The SEBM technique now allows for the exact production of a desired geometry to analyze and evaluate all the established correlations between, e.g., the pressure drop and porosity and surface area [20].

In this regard, in the present contribution POCS prepared by SEBM with ideal cubic cell geometry (icPOCS) as one of the simplest geometries of a RUC were used for a systematic investigation to characterize the influence of (a) porosity and/or (b) tortuosity on the pressure drop behavior independently, which both can easily be modified simply by (a) adjusting the cell dimensions or by (b) changing the orientation of the RUC perpendicular to the main direction of the flow. To the best of our knowledge, neither a systematic study of the pressure drop behavior of such icPOCS in

Table 1
Overview of the icPOCS investigated.

Cells per inch (CPI)	Tilt-angle/°		Remarks	Samplename
	x-Axis	*y*-Axis		
5	0	0		5CPI
9	0	0		0-0-9CPI
	15	0		15-0-9CPI
	30	0		30-0-9CPI
	45	0		45-0-9CPI
	30	30		30-30-9CPI
11[a]	0	0	Low porosity	11CPI-lp
	0	0	High porosity	11CPI-hp

[a] different strut diameters.