Chemical Engineering & Processing: Process Intensification 127 (2018) 36–42

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Pressure drop and heat transfer properties of cubic iso-reticular foams

Núria F. Bastos Rebelo[a], Kari Anne Andreassen[a], Luis I. Suarez Ríos[b], Juan C. Piquero Camblor[b], Hans-Jörg Zander[c], Carlos A. Grande[a,*]

[a] SINTEF Industry, P.O. Box 124, Blindern, N0314 Oslo, Norway
[b] PRODINTEC Parque Científico Tecnológico de Gijón, Avda. Jardín Botánico, 1345, 33203 Gijón, Asturias, Spain
[c] LINDE AG, Engineering Division, Dr.-Carl von Linde Straße 6-14, 82049 Pullach, Germany

ARTICLE INFO

Keywords:
Additive manufacturing
Foams
Aluminum
Heat transfer
Pressure drop

ABSTRACT

With the aid of additive manufacturing is now possible to create customized reactors and reactor internals with desired targeted properties that can be used for multiple purposes in reaction and separation processes. One interesting possibility regarding manufacture of foams is indeed the possibility to construct fully iso-reticular foams where the residence time, pressure drop and heat transfer properties can be tuned for specific reactions.

In this work we present the design, manufacturing and characterization of cubic-cell foams 3D printed in aluminium as a simpler case of geometric iso-reticular design. The results indicated that full shape control and desired porosity are achieved covering porosity values between 0.72 to 0.95. Moreover, the foams have a high surface area per unit volume while presenting a very small pressure drop. Additionally, the possibility of connecting the foams to an external layer makes them very good heat transmission devices with many possible applications in removing or conducting heat to increase conversion of very exothermic or endothermic reactions.

1. Introduction

The utilization of structured catalysts has provided great advantages to catalytic reactors. When compared to random packings, structured packings render smaller pressure drop and faster heat transfer [1]. Among structured packings, foams are particularly interesting structures because they can have a high porosity and thus low pressure drop across them [2–4]. But the most interesting feature from foams is that they have a high degree of interconnectivity that can promote radial mixing which will enable improved heat transfer and mixing of reactants. Indeed, foams with porosity over 90% are already produced, with impressive low pressure drop and capabilities to simultaneously promote heat transfer and radial mixing.

Open-cell foams are cellular materials connected by solid struts. Generally, they are produced by expansion of polymers (mostly polyurethane). Supports for catalytic foams are fabricated using a polyurethane foam with the material as a slurry, followed by several specific steps to load the desired materials and finishing with a thermal treatment to remove the polymer [5]. The voidage of each cell differs accordingly to the details of the method of preparation but in most cases, the cell shape is pseudo-spherical [6]. Even when many parameters are controlled in current manufacturing processes, it is impossible to obtain perfect iso-reticular foams; either it is not possible to completely tailor the shape of the cells or the thickness of the struts and/or the local porosity. Having a slight random distribution of cell volumes and strut dimensions present some drawbacks in very exothermic or endothermic reactions. The most important ones are the lack of full control of reactant path and residence time in the foam that can lead to selectivity issues or to hot (or cold) spots.

Additive manufacturing (AM) or 3D printing is an advanced methodology for producing complex shapes layer upon layer. The creation of the object is additive, which contributes to the economy of resources when compared with classical manufacturing (that can be termed as negative manufacturing). The statement of resource economy is true at least when the parts do not need an external or internal complex support structure to be printed.

Using AM, the process of manufacturing is digital; the first item of the process is a. stl or. obj file designed in a computer software and transferred to a 3D printer (or similar machine) that converts it to the desired object. The utilization of AM has brought possibilities of fabricating pieces with complex shapes that were not achievable with other methodologies. A manual part of manufacturing can take place afterwards since finishing and polishing could be necessary.

The utilization of AM is slowly penetrating into chemistry and chemical engineering [7–10]. Initial steps were made printing some parts, mostly in polymers to demonstrate the possibility of the technique. Examples of iso-reticular foams are indeed presented in many places as demonstrators of what 3D printers can do. Metallic foams

* Corresponding author.
E-mail address: carlos.grande@sintef.no (C.A. Grande).

https://doi.org/10.1016/j.cep.2018.03.008
Received 31 August 2017; Received in revised form 5 March 2018; Accepted 9 March 2018
Available online 12 March 2018
0255-2701/

Nomenclature

ε_c	Porosity of the cell
d_{int}	Internal length of the cell (m)
l	Strut width (m)
A_c/V	Ratio of area per unit volume of the foam (1/m)
Δp	Pressure drop (Pa)
p	Pressure (Pa)
η_f	Dynamic viscosity of the fluid (Pa s)
d_p	Diameter of the particles (m)
ρ_f	Density of the fluid (kg/m^3)
f_{mod}	Modified friction factor
f	Friction factor
$Re_{p,mod}$	Modified particle Reynolds number
Re_c	Cell Reynolds number
Re_p	Particle Reynolds number
Eu	Euler number
$u_{f,0}$	Superficial velocity of the fluid at the entrance of the foam (m/s)
d_i	Internal diameter of the tube (m)
d_0	External diameter of the tube (m)
$C_{p,f}$	Specific heat capacity of the fluid (J/kg K)
Nu	Nusselt number
Pr	Prandtl number
α	Hat transfer coefficient (W/m^2 K)
L	Length of the foam (m)
Z	Axial coordinate for calculation of heat transfer coefficient (m)
λ_g	Gas heat conductivity (W/m K)

have already been fabricated using additive manufacturing [11,12]. Indeed, one of these works report Ti-based cubic cells demonstrating that orientation of the cells can result in different flow properties [12]. Being able to control the shape of individual cells in open-cell foams can lead to unprecedented advance in utilization of tailored foam structures, particularly in reaction and separation engineering. In this regard, the main advantage of additive manufacturing is that it has unlocked the possibility of design the foams before their current manufacturing. This means that the new manufacturing technique does not only affect the methodology to produce the actual foam, but most importantly, it affects the way that the foam is designed.

In this work we have focused on the design, characterization and testing of cubic-cell iso-reticular foams printed on aluminium AlSi10Mg. Cubic cells were chosen because they are one of the simplest shapes that can be used to study the effect of the different design parameters for transport of heat and momentum. We have printed eight different foams varying the cell and strut dimensions as well as the angular rotation of the cells relatively to an external cylindrical cover that allow us using the foams for direct measurements of pressure drop and heat transfer. Measurements were made using air as fluid passing through the foam covering velocities from 0 to 20 m/s.

2. Theoretical

The main advantage of using additive manufacturing for fabricating foams is that a detailed and targeted design has to be accomplished beforehand.

From the large possible amount of designs achievable [13], we have started studying an array of cubic cells. A foam designed with cubic iso-reticular cells has at least four degrees of freedom: strut width (l), internal length of the empty cell (d_{int}) and angles of rotation in two dimensions as shown in Fig. 1. To generate a foam, the cell is designed with specific parameters and replicated until it occupies the desired volume, which in this case is a cylindrical tube with one inch external diameter (wall thickness of 1 mm) and with 100 mm length. Eight different foams were designed varying the different parameters described

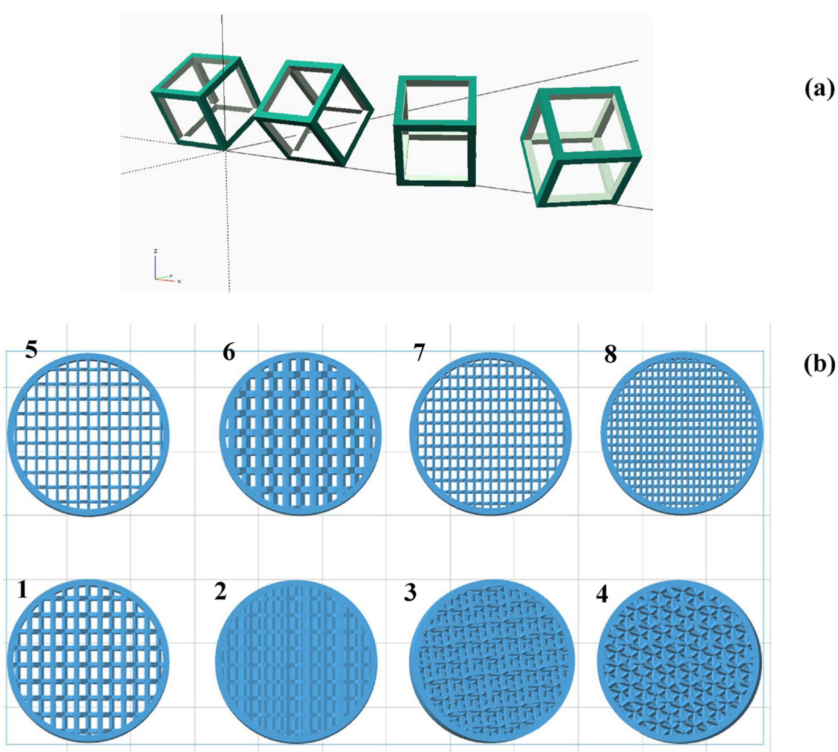

Fig. 1. (a) Angular rotation of the cubic cell used in this work and (b) orientation in the 3D printing software of the different foams produced.