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# Numerical study of cell morphology effects on convective heat transfer in reticulated ceramics

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ABSTRACT

Understanding the influence of foam morphology on the heat transport mechanism is an essential task for the design engineers. The assessment of foam thermal properties was performed using experimental techniques or simulation approaches such as Finite Elements analysis and/or computational fluid dynamics and was, up to now, mainly focused on describing the influence of some average parameters, such as cell size and porosity. Recent numerical analysis have instead demonstrated that local cell morphological structures can strongly influence thermal conduction in ceramic foams. Therefore, in the present work, the effect of morphological characteristics, namely ligament radius, cell inclination angle and ligament tapering, on the convective heat transfer of ceramic foams were studied. The approach used is Computational Fluid Dynamics (CFD) and foam geometries were schematically represented with tetrakaydecahedra geometries. The numerical simulations, performed with ANSYS/Fluent on different tetrakaydecahedra geometries, aimed at evaluating pressure drop and heat exchange through the foam. A heat exchanger efficiency parameter was defined and then evaluated for the different foam geometries at several air flow velocities. Results show the influence of the different morphological parameters and, in particular, that the heat exchanger efficiency of the foams decreases when increasing the air flow velocity.

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## 1. Introduction

Among the so called hybrid materials, cellular structures and foams stand for their outstanding effective properties resulting from the combination of two or more materials, or of materials and space [1]. Synthetic foams in general are widely employed in many industrial applications including: filtration, personal safety, and packaging [2], aeronautics [3], and aerospace [4].

Reticulated ceramics are highly porous open celled ceramics commonly manufactured by the replica method. Replica ceramics are produced in three steps: dipping a polymeric foam into a suitable ceramic slurry, de-binding and then sintering [5]. Their fabrication method is relatively economic, and large parts can be produced. Process parameters do influence the properties of the foam: by changing the slurry viscosity or by repeating the dipping phase several times, the strut (or ligament) thickness (i.e., porosity) can be accurately adjusted. The morphology of the foam cells and strut tapering are other two foams parameters studied in this work. They can be modified during foaming of the polymeric templates used for replica [2] or, as for cells stretching direction, it can be selected by cutting oriented smaller pieces from a bigger block. More recently, replica was also applied on engineered polymer scaffolds obtained by 3D printing [6].

Advanced ceramics are extensively applied as constituent materials for ceramic foams [7]. In particular silicon carbide highly porous reticulated ceramics, thanks to their open interconnected porosity and superior thermo-mechanical properties [8,9], are used for high temperature applications where a very hot fluid flows through their porosity. These applications are: porous burners [10–13], catalytic reactors supports [14,15] and concentrated solar absorbers [16,17].

Reticulated Si–SiC foams are characterized by an interconnected network of intercommunicating cells whose edges are made of solid ligaments. The flowing fluid behavior through the cells, and the associated convective heat transfer between the ligaments outer surface and the fluid has been widely studied in the past years.

The numerical modeling approaches used to describe these phenomena can be divided in two major classes:

- Local thermal equilibrium (LTE) models [18], where fluid and solid phases are in local thermal equilibrium.
- Local Thermal Non-Equilibrium models, which assumes that there is a finite temperature difference between the fluid and the solid phase [19].

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**Nomenclature**

| | | | |
|---|---|---|---|
| $A$ | Area of the foam surface, $m^2$ | $T$ | Temperature, K |
| $D$ | Tetrakaydecahedron cell width, m | $T_{f,avg}$ | Fluid average temperature, K |
| $h$ | mean convective heat exchange coefficient, $W/m^2K$ | $T_{f,in}$ | Fluid inlet temperature, K |
| $H$ | tetrakaydecahedron cell height, m | $T_{f,out}$ | Fluid outlet temperature, K |
| $k$ | Turbulent kinetic energy, $m^2/s^2$ | $T_s$ | Foam surface temperature, K |
| $L$ | Length of the major tetrakaydecahedron ligament, m | $v$ | Fluid specific volume, $m^3/kg$ |
| $L_C$ | Length of the schematic foam element, m | $\theta$ | Tetrakaydecahedron inclination angle, degrees |
| $\dot{m}$ | mass flow rate, kg/s | $\varepsilon$ | rate of dissipation of turbulent energy, $m^2/s^3$ |
| $p$ | pressure, Pa | $\omega$ | frequency of large eddies, $s^{-1}$ |
| $\dot{Q}$ | heat flux, W | $\eta_{th}$ | Heat exchanger efficiency, – |
| $R_{ex}$ | Cell ligament radius at the node, m | $\eta^*_{th}$ | Heat exchanger efficiency, – |
| $R_{min}$ | Cell ligament radius at its center, m | $\rho$ | Fluid mass density, $kg/m^3$ |
| $t$ | Cell ligament tapering, – | | |

Experimental data acquisition was diffusely utilized to characterize fluid flow and heat transfer in foams. The first attempt can be traced back to Darcy's work on porous media. More recently, Paek et al. [20] studied thermo physical properties of highly porous aluminum foams; they found that, for a given porosity value, the decrease of cell size resulted in the increase of the surface area to volume ratio with consequent increase of flow resistance and pressure drop. According to the reported results they demonstrated that permeability is influenced by both porosity and cell size.

Bonnet et al. [21] established simple relations between flow and morphological parameters of metallic foams, concluding that just pore size can be sufficient for the description of flow laws in such highly porous materials. Hwang et al. [22] studied the heat transfer and friction factor in a duct filled with aluminum foams with porosity in the range of 70–95%. These authors concluded that friction factor and volumetric heat transfer coefficient increase with decreasing sample porosity for a given Reynolds number. A similar work was performed by Boomsma and Poulikakos [23] which compressed 40 PPI aluminum foams to obtain samples with different porosities and tested them under forced convection using water as working fluid. They observed that the structural differences, generated by compressing the specimens, did not have a noticeable effect on permeability. Based on these observation, Boomsma et al. [24] experimentally evaluated the heat exchange performance of foams.

The present work describes how, beside porosity and cell size, foam cell parameters such as cell inclination, foam ligament shape and cross section can influence its convective performances. As recently shown, these parameters can be purposely modified to design and produce engineered cellular ceramics [6].

In this work, foam morphology effects on convective heat transfer were studied by using CFD simulations of an air flow passing through a foam sample which was schematically described by three tetrakaydecahedra cells; the effects of variation of cell inclination angle, ligament tapering and external ligament radius were analyzed.

## 2. Foam representation

Reticulated ceramic foams can be described as a lattice of open cells with typically 12–14 pentagonal or hexagonal faces. Many idealized geometries, with different complexity, were used in the literature to represent and study foam thermal behavior. One of the simplest model is a lattice of repeating cubic cells [25]. More accurate models, such as Weaire–Phelans cells [26] and the tetrakaydecahedra [27] were also used to numerically evaluate the pressure drop and convective heat transfer in foams [25]. The Weaire–Phelan cell is theoretically more efficient in representing the complex foam structure compared to the tetrakaydecahedral one; however, the very limited advantages, and the increased complexity in building such kind of complicated geometries makes the tetrakaydecahedra cell the most widely used [25]. Due to the foaming process of the template foam, a better cell representation is given by the elongated tetrakaydecahedron, a polyhedron composed of 14 faces and 36 edges (Fig. 1). To unambiguously define its geometry, the basic geometrical parameters and correlations were calculated by Sullivan et al. [28] (see Table 1).

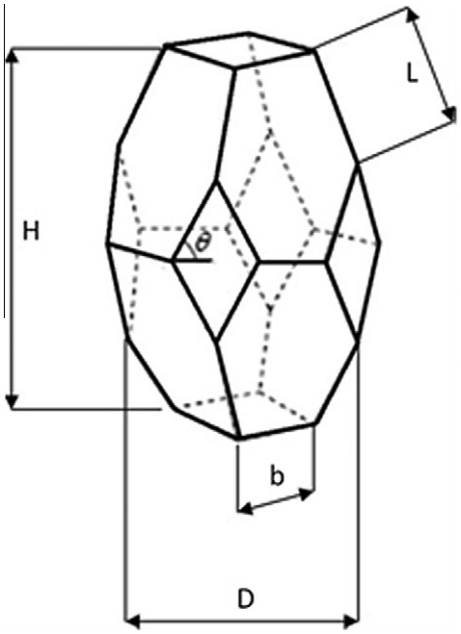


**Fig. 1.** Tetrakaydecahedron cell.

**Table 1**
Main tetrakaydecahedron parameters [28].

| Parameter | Description |
|---|---|
| $H = 4L\sin\theta$ | Cell height [mm] |
| $D = 2\ L\cos\theta + \sqrt{2}\ L \cdot b/L$ | Cell width [mm] |
| $L$ | Length of the major ligament [mm] |
| $b/L$ | Ratio between ligament lengths |
| $\theta$ | Inclination angle (degrees) |

In CFD studies found in the literature so far, foam structure has been mainly represented as a lattice of repeating tetrakaydecahe-

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