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Direct Numerical Simulation of heat transfer in SMSP regenerative combustion chamber

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Abstract

The realization of a regenerative thrust chamber assembly using the Additive Layer Manufacturing technology allows to design a cryogenic combustion chamber for space application characterized by a cooling system made of reticular structures with the Single Material Single Part (SMSP) concept, going beyond the structural limitation represented by the classical concept of cooling system composed of channels and ribs. The need to build a complex structure to enhance the cooling system performance derives from Inconel718, the material used to print the ALM combustor. Despite excellent structural properties, this material has relatively low thermal conductivity. Due to the extreme geometrical complexity of the innovative cooling system, Direct Navier Stokes simulations relying on the immersed-boundary technique are carried out to achieve reliable performance estimation. Several types of reticular geometries have been investigated in order to characterize the behavior of the heat thermal exchange coefficient, aiming to optimize the efficiency of the cooling system. An experimental test campaign has been carried out on cylindrical samples containing the different geometries in order to investigate the pressure drop across the reticular structures. SMSP is a self-financed project promoted by AVIO S.p.A., that is the owner of the related international patent.

1. Introduction

The scope of the research activity herein presented is to carry out a CFD analysis of the SMSP structured foam, to be implemented in the first prototype of the cylindrical part of a regenerative combustion chamber. The item to be used for this activity is made up of a hollow cylinder with a length of 200 [mm] and an internal diameter of 2 [in], filled with structures similar to turbine blades, designed so as to prevent fluid stratification inside the cooling channel, thus enhancing the heat transfer between fluid and metal. A CFD activity on the SMSP cylindrical samples and combustion chamber is herein carried out using Direct Numerical Simulation (DNS) of the Navier-Stokes equations for the fluid phase, coupled with solution of the Fourier equation for the temperature field inside the metal phase. DNS is applied to various sample geometries, with the aim of fully characterizing the complex flow inside these structures, and to predict pressure losses and heat transfer rates. Preliminary activities are initially carried out in a simplified doubly-periodic configuration, which will be used to gain confidence into the mesh resolution and domain size needed to achieve grid-independent results. The code is then used to rebuild the flow cases actually tested in the AVIO experiments, thus also including the cylindrical container. The activities are carried out using water as cooling fluid, and include simulations aimed at thermal characterization on the SMSP combustion chamber.

2. Reticular structures description

The reticular structures investigated in this analysis are six different combinations of base modules composed of blades and turbulator elements (C01; C02; D01; D02; E01; E02). The blade elements have the role of convey the coolant flow from the upper to the lower wall of the cooling system acting as stator blades, while the turbulators have the role of enhance the mixing. All the modules differ each other in terms of angle of attack and distance between blade and turbulator elements (Figure 1).

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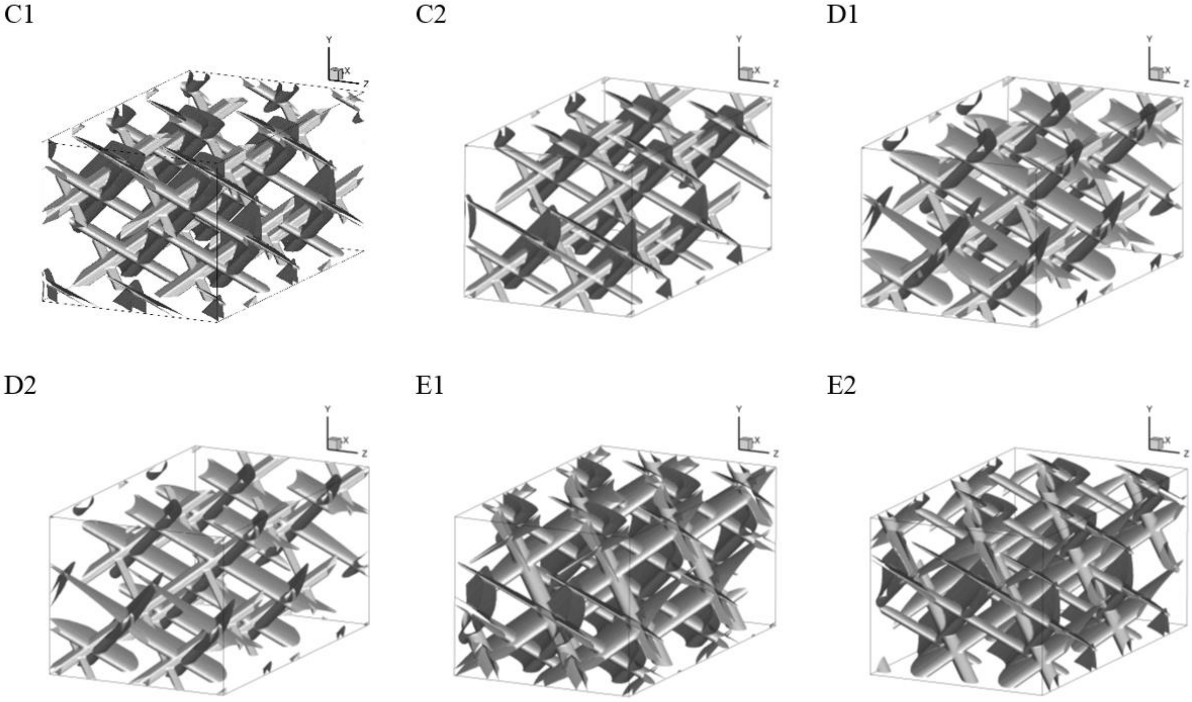

Figure 1: Reticular structures from all the six base modules geometry.

3. Methodology

The CFD activities rely on direct numerical simulation (DNS), namely simulation of the Navier-Stokes equations in their unsteady, three-dimensional form, with sufficient resolution to resolve all the scales of turbulent flow motion, down to the dissipative (Kolmogorov) scale. The boundary conditions at the surface of the reticular structure are handled through second-order interpolation, taking advantage of the immersed-boundary technique (Orlandi and Leonardi, 2006). The temperature field within the solid phase is estimated based on the Fourier equation, assuming isotropic thermal conductivity.
The equations are discretized in a Cartesian coordinate system (x, y, z denote the stream-wise, wall-normal and span-wise directions, respectively) using staggered central second-order finite-difference approximations, to guarantee that kinetic energy is globally conserved in the limit of inviscid flow. Time advancement is carried out by means of a hybrid third-order low-storage Runge-Kutta algorithm coupled with the second-order Crank-Nicolson scheme combined in the fractional-step procedure, whereby the convective terms are treated explicitly and the diffusive terms are treated implicitly, limited to the wall-normal direction. The Poisson equation for the pressure field stemming from the incompressibility condition is efficiently solved through Fourier transform-based methods (Kim and Moin, 1985). A full description of the algorithm is provided in Orlandi (2012).

4. Grid sensitivity

Preliminary DNS have been carried out with the purpose of establishing the sensitivity of the numerical results to mesh spacing, as well as to the size of the computational box, limited to the case of the C01 foam, and at low Reynolds number, $Re_L = 250$. It appears that the pressure gradient converges very quickly to its asymptotic value, on a time scale of about ten non-dimensional units. After this initial transient the resistance starts to oscillate around a nearly constant value which slightly differs as the grid resolution is varied. The results are shown in Figure 2.

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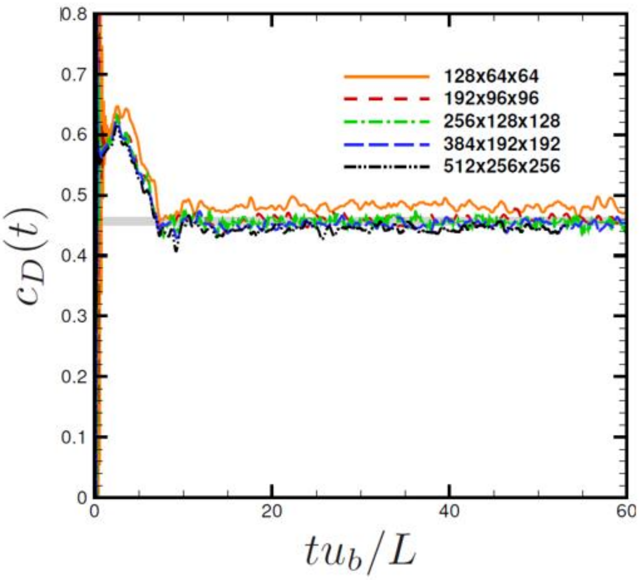

Figure 2: DNS in doubly periodic domain: time history of drag coefficient for C1 foam at ReL = 250 on grids with different resolution.

5. Analysis of pressure drop

This section contains a summary of the results obtained for the pressure drop with DNS of structured foams in periodic channels. Several mass-flow-rates have been considered, corresponding to mean velocities (u_b) from 0.25 to 4 [m/s]. As expected, all foams exhibit a decreasing trend with the Reynolds number, although with significant differences. In particular, the figure predicts that the E01, E02 foams which have large drag at low speed, should become more efficient at higher flow speed. To get further insight into the behavior of various foams, and to provide formulas of practical use for pressure drop prediction also outside the range of flow conditions reached with DNS, data fits have been derived. Two types of functional representations have been considered, namely that associated with the Darcy-Forchheimer formula for porous media

$$c_D = c_{D0} + \beta Re_L^{-1}, \tag{4}$$

and a power-law representation appropriate for flows over smooth surfaces,

$$c_D = k Re_L^{-\alpha}. \tag{5}$$

Based on a dedicated calibration for coefficient of the drag formulas of the various structured foams, the pressure drop in a duct with length L_x can be easily evaluated as

$$\Delta p = \frac{1}{2}\frac{L_x}{L}\rho u_b^2 c_D(Re_L), \tag{6}$$

where ρ is the fluid density.

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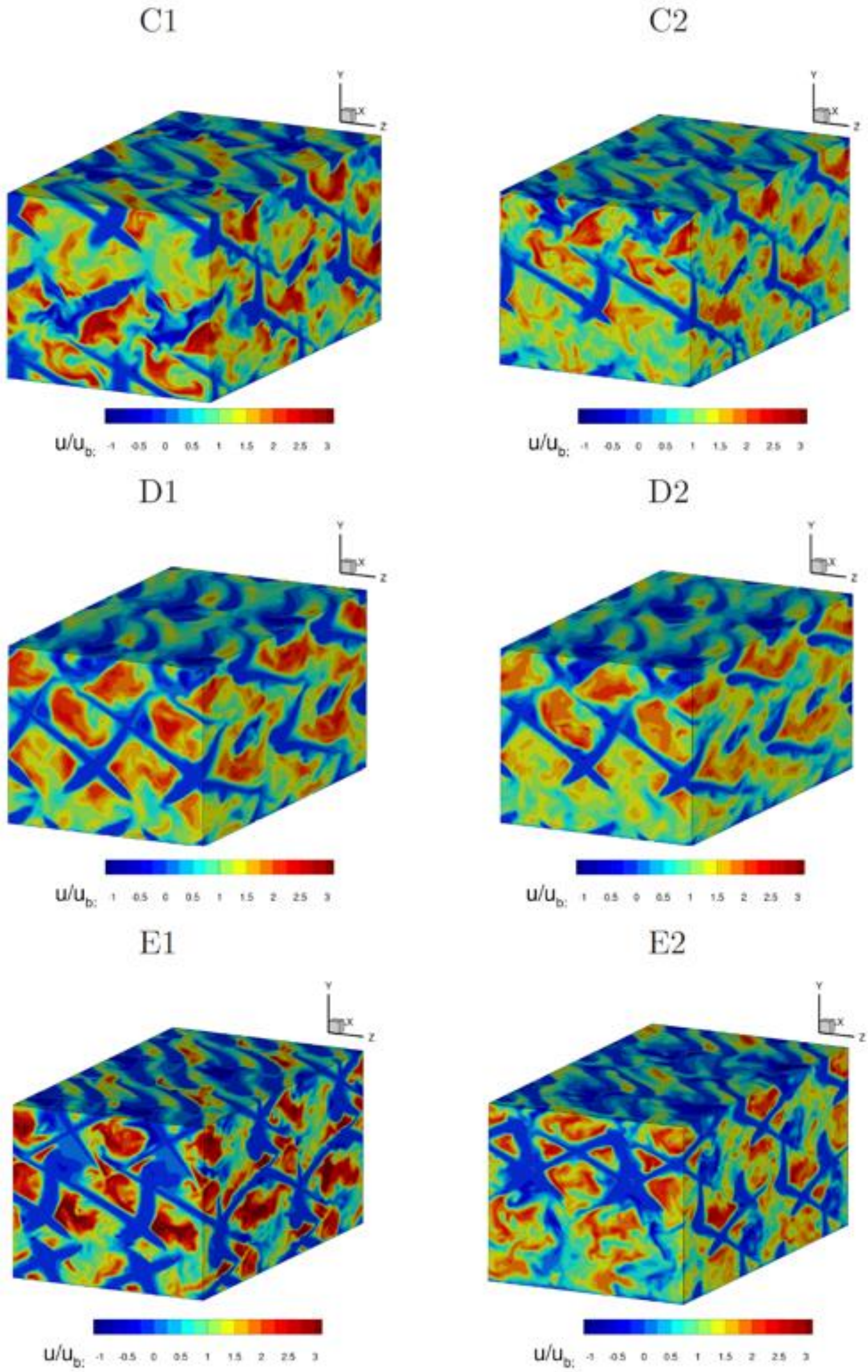

Figure 3: Stream-wise velocity contours for DNS in doubly periodic domain at ReL = 250.

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6. Analysis of heat transfer

Heat transfer in the periodic foam geometries has been studied by solving the heat equation in addition to the Navier-Stokes equations. For that purpose, we assign uniform heat flux q_w at the bottom wall whereas the upper wall is adiabatic, to approximate the conditions found in the cooling channels of rocket engines.
The heat transfer is conveniently expressed in non-dimensional form in terms of the duct Nusselt number, defined as

$$Nu = \frac{q_w h_e}{\lambda_f(\theta_w - \theta_b)}, \tag{8}$$

where q_w is the wall heat flux, $h_e = h \cdot \varepsilon$ is the effective duct height, ε is the duct porosity (i.e. ratio of fluid available volume to total), θ_w is the wall temperature, θ_b is the coolant bulk temperature, and λ_f is its thermal conductivity. As for the pressure drop, a grid sensitivity study has been carried out for the heat transfer coefficient at $Re_L = 250$, whose results are presented in Figure 4(a), which basically confirms the estimates for the necessary grid resolution made regarding to Figure 2 (a). The figure also shows that the thermal field requires much longer time velocity field to achieve statistical convergence, hence the computational effort is even more substantial. A comparison of the Nusselt number time history for the various foam geometries is reported in Figure 4(b), which shows significant difference among the various foams under scrutiny. A series of numerical simulations have then been carried out to characterize the variation of Nu at developed flow conditions with the Reynolds number. By analogy with the classical Dittus-Boelter formula, functional relationships of the type $Nu = Nu(Re_b)$ have been sought for, where $Re_b = h_e u_b/\nu$ is the duct bulk Reynolds number. In particular, we consider the Dittus-Boelter power laws equation. The heat transfer coefficient for the fluid system is readily found according to

$$H_f = \frac{q_w}{\theta_w - \theta_b} = \frac{Nu \cdot \lambda_f}{h_e}. \tag{9}$$

Typical temperature cross section in the cooling channel is shown in Figure 5.

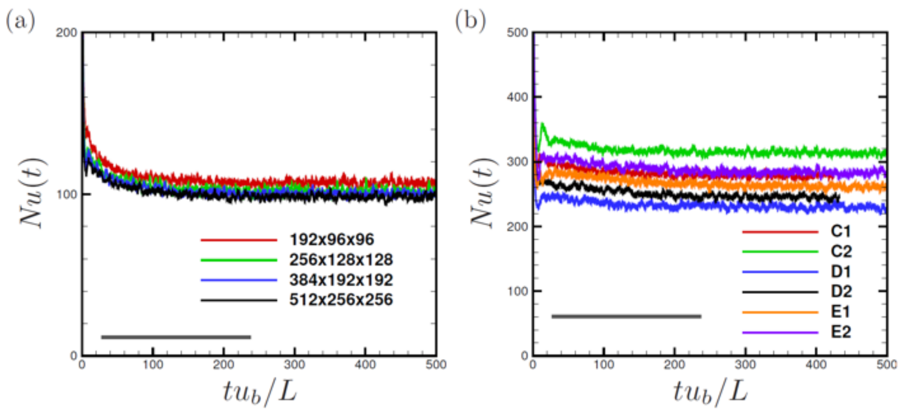

Figure 4: Time history of Nusselt number for doubly periodic DNS: (a) grid resolution study at ReL = 250; and (b) effect of foam geometry at ReL = 1000. The horizontal grey lines indicate the expected Nu for the case of a smooth channel at the same Reynolds number.

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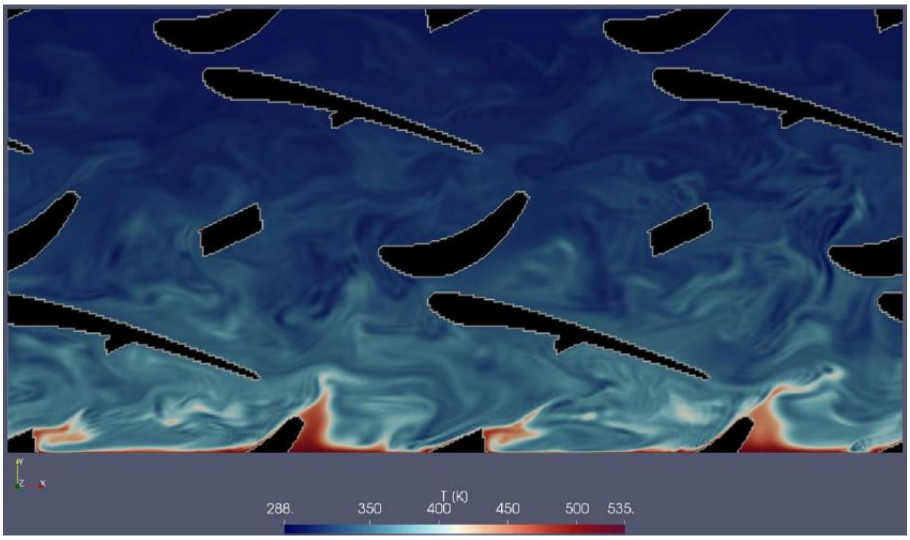

Figure 5: Non-dimensional temperature field.

7. DNS of foam inside circular pipe

Numerical simulations have been carried out for the actual cylindrical duct geometry considered in the AVIO experimental campaign (see Figure 6). Based on the outcomes of DNS in periodic domains, only two stream-wise repetitions of the basic module have been considered. Yet, given the large number of elements in the cross-stream (y − z) plane, numerical simulations of this configuration are very demanding. DNS have been carried out for two values of the unit Reynolds number, namely $Re_L = 250$ and $Re_L = 1000$. Representative flow visualizations are shown in Figure 7. The computed pressure drop is compared with the experimental tests carried out by AVIO. The data show satisfactory agreement between simulations and experiments, which supports DNS as an efficient tool to rank the hydrodynamic properties of structured foams.

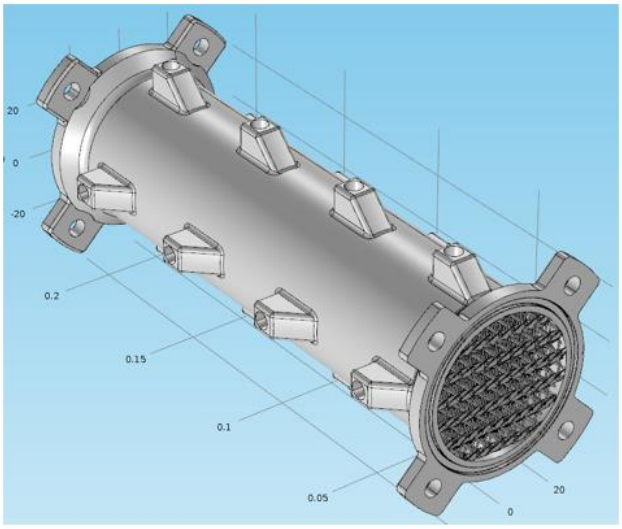

Figure 6: Foam geometries for DNS in cylindrical domain.

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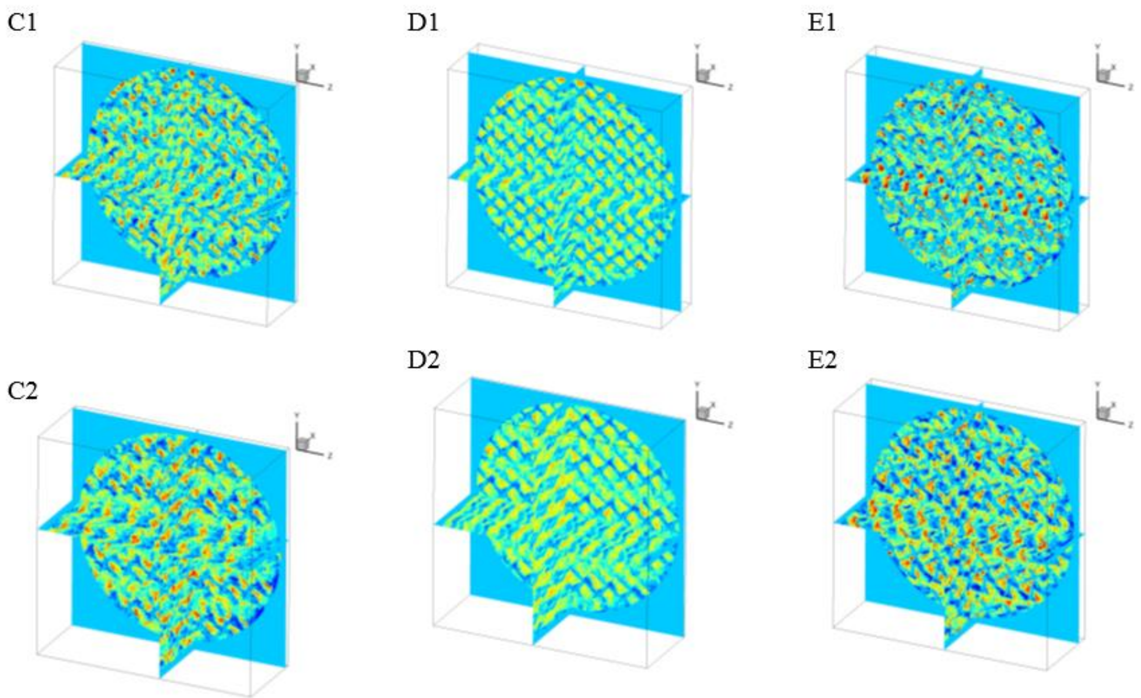

Figure 7: Streamwise velocity contours for DNS in cylindrical domain at ReL = 250.

8. Thermodynamic efficiency

The thermodynamic efficiency of the proposed structured foams, and of any cooling channel in general, is defined by introducing a dedicated metric, defined in general terms as the ratio of the actual heat flux to the heat flux which would be achieved with an axial smooth channel carrying the same mass-flow-rate with the same pressure drop, hence requiring equal pumping power. Estimation of thermal efficiency requires the knowledge of expressions for the friction coefficient and the Nusselt number for a smooth channel, which we have found by fitting DNS data for axial channels at various Reynolds numbers, which are slightly different from the classical power-law fits of Blasius and Dittus-Boelter. Similarly, an efficiency factor may be defined for given mass-flow-rate and heat flux, and defined as the ratio of the needed pumping power versus the value for a smooth channel.
The performance of the structured foams shows heat transfer increase relative to an equivalent smooth channel, as a function of the corresponding increase of the pressure drop, at different Reynolds numbers ($250 \leq Re_L \leq 4000$). As expected, there is a strict correlation between the two quantities, indicating that heat transfer enhancement implies greater pressure losses. In terms of thermodynamic efficiency of the various foams, we noticed for some foams a similar behavior was previously reported for flow in random metal foams (Bai and Chung, 2012). Of course, thermodynamic efficiency is not necessarily the only, nor the 'best' parameter to judge on the practical effectiveness of foams, as their actual performance can only be judged once their pressure drop and heat transfer performance maps are inserted into the actual functional diagram of the whole propulsive system.

9. Flow visualizations

In this section we report flow visualizations, obtained with the software Paraview. In order to enhance the flow path visualization, it has been used the Line Integral Convolution to visualize the velocity vector field (see Figure 8). In this way it is possible to highlight more clearly the vortex structures inside the computational domain. The iso-contour surfaces are used in order to see the vorticity magnitude in three dimensions (see Figure 9).

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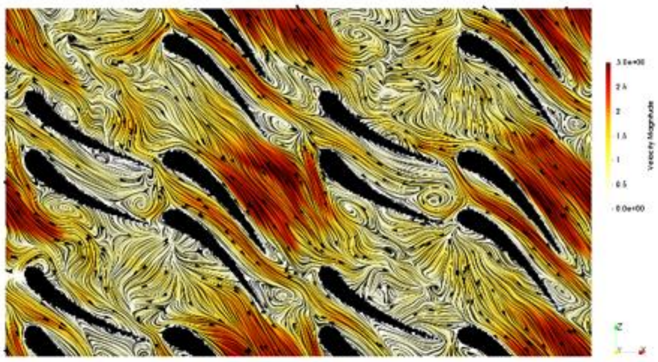
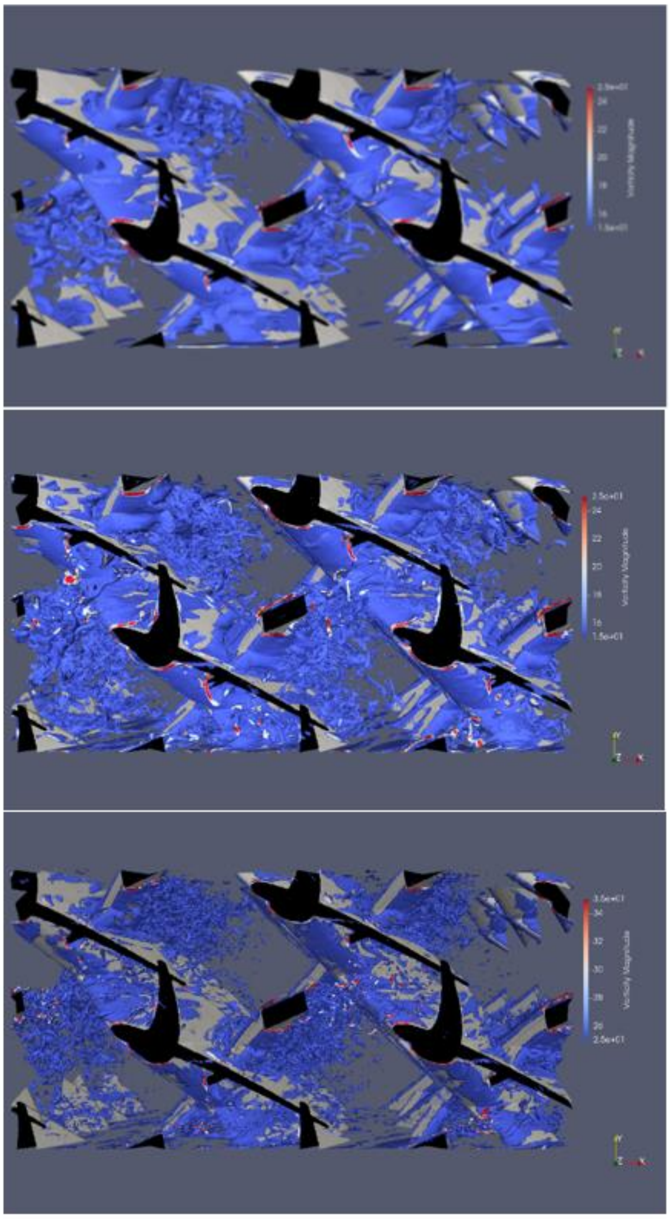


Figure 8: Line Integral Convolution visualization of the velocity vector field.



(a)

(b)

(c)

Figure 9: Vorticity iso-surfaces at ReL = 250 (a), ReL = 500 (b), ReL = 1000 (c).

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Conclusions

A DNS solver has been developed and tested for high-fidelity thermo-fluid dynamic simulation of flows in configurations representative of a rocket engine revolutionary cooling system made using the additive layer manufacturing (ALM) technology. Good agreement with reference 'cold' experiments carried out in a cylindrical pipe has been obtained, with remaining discrepancies likely due to imperfect surface finishing in 3D printing, not accounted for in the DNS. An important finding of the activities is that DNS in small domains and at relatively low Reynolds number are sufficient to qualify the performance of a certain type of foam with respect to other, both in terms of associated drag and heat transfer. Functional fits are obtained for the drag coefficient and for the heat transfer coefficient of all the proposed structured foams as a function of the Reynolds number, which can be directly exploited for cooling channel design. An efficiency metric has been defined to judge on the thermodynamic efficiency of the foams, based on the heat transfer enhancement with respect to the case of a smooth channel, for given pumping power.

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