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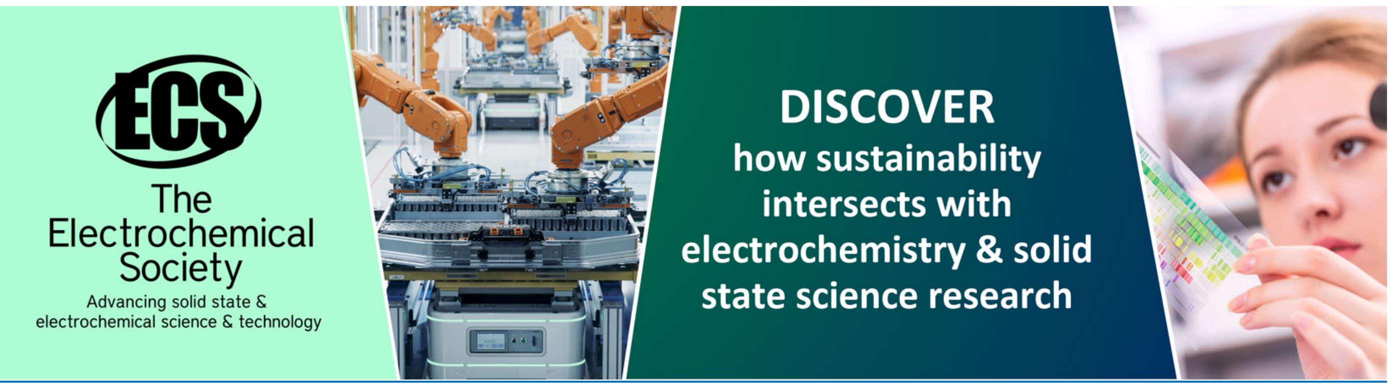

# Preliminary design and modeling of mini channels to enhance heat transfer in a millimetric catalytic combustor

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**Abstract.** Mini channel solution is used in devices that require a high density of transmitted thermal power as a very large-scale integration design in computer systems and compact exchangers. Furthermore, the mini channels are extensively investigated in the literature for turbulent and laminar regimes. In this project, different configurations of mini channels have been studied to enhance heat transfer, using simulations with a commercial multi-physics code. Thanks to the results of the models, more promising configurations with 3D printing technique may be built. The project challenge is improving convective thermal power extracted by the exhaust gases of a mini-catalytic combustor. The combustor feeds six modules for thermoelectric power production (TEMs). As the first step, three different mini channel geometries have been chosen; the first one with 19 channels with rectangular cross-section, the second one with 6 channels with a convergent profile, and the latter with 2 channels with a fractal branching geometry. Simulations started from studying fluid dynamic to investigate the velocity field at the exit of the mini channels. The analysis has been extended by adding the conjugate heat exchange between fluid and combustor wall. The results show an increase in heat exchange compared to the base case for all configurations, with a maximum value for the 19 mini channels configuration.

**Key Words**: *forced convection, thermoelectric generator, mini channels*

## 1. Introduction

The problem of power supply for decades is no more just about the production and distribution of electricity on a large scale. The development of electronics and the increasing demand of this market, with systems ranging from integrated circuits to microsensors, have opened up the need to power devices with the greatest possible autonomy that requires electric power in small dimensions [1]. The traditional solution to provide electricity to these products is storage through batteries. Batteries need replacement, when after a series of charge and discharge cycles, they are no longer performing. Thermoelectric generators (TEGs) are a remarkable alternative [2]. The thermoelectric phenomenon is based on the passage of charges in two types of semiconductors: type-n and type-p, which lead to the generation of voltage due to an imposed temperature gradient (Seebeck effect) and vice versa (Peltier effect). Since 1959, when General Motors launched the first thermoelectric module (TEM) which

couples the semiconductors thermally in parallel and electrically in series, it has been possible to develop power generators that exploit this phenomenon [3].
Thermoelectric generators have ideally infinite service life, carrying out a direct conversion of thermal power in electrical power, without the aid of moving parts. Being solid state generators, their high reliability and durability, it has made them the focus of a renewed scientific interest. In addition, their modularity allows them to be used for applications of varied dimensional scales without losing in performances. On the other hand, the great limitation of this technology lies in the low efficiency of thermoelectric modules which, for commercial solutions, always ranges between 5 and 9% [4]. For all these features, they are in no way comparable to traditional large engines with high efficiency, but on small dimensional scales - at small powers and temperature differences - they become the most advantageous solution [5].

### *1.1. TEG prototype*

The prototype of a TEG has been studied on a millimetric scale. The device, like those built previously [6], has been designed to replacing common power banks solution for smartphones. The challenge of its design is to create a safe, reliable, and portable system. With the scope of creating a marketable device, it is necessary to increase the initial performances as much as possible. It has been decided to reduce the problems that affect the efficiency of the modules by raising the heat transfer in the hot side system.
The TEG operates via six commercial modules in Bismuth-Tellurium of size 18·18 $mm^2$. TEG's dimensions are 75 mm in diameter to 21 mm in height and a total weight of 400g. The system is propane fueled. The choice of propane is due to its high calorific value and the commercial availability of small propane tank for refilling lighters. The premixed fuel and air in stoichiometric conditions are injected into the bottom of a hexagonal combustion chamber. The chamber is built exploiting additive manufacturing technique in SS316L (Figure 1). The gas mixture reacts on 52 cylindrical platinum pellets to coat an inert alumina support. The catalysis allows to reach lower combustion temperatures than traditional flame combustion and to obtain a safer process that can be coupled with the TEMs, which have operating temperatures that cannot exceed 300°C. The exhaust gases are piped to the walls where they exchange with the hot face of the modules, providing the thermal power needed for the generator. To manage the temperature difference between the faces of the thermoelectric module, the TEG is equipped with six water cooling circuits made on polymer through the fuse deposition melting technique. For the optimization of the cold side system authors have built serpentine ducts with an unconventional section in previous work [7]. The prototype thus constituted generates a total power of 9 W with an efficiency of 3.5%.

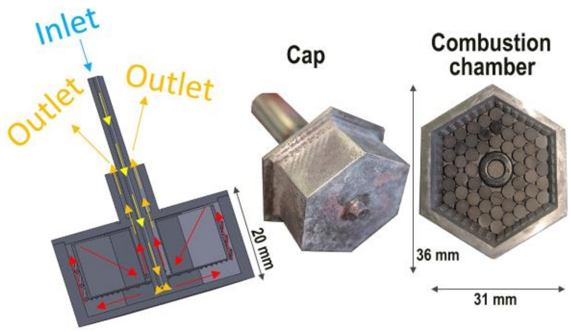


**Figure 1.** Details of the 3d printed TEG's catalytic combustor: the total drawing with the flow circuit description (on the left), the sealing cap (central) and the arrangement of the pellets in the bottom of the chamber with dimensions(right).

### *1.2. Aim of the project*
To increase the current generator performance, new heat transfer enhancement solutions have been evaluated. Specifically, the focus has been on designing mini channels solutions at the interface between combustor and TEMs. Mini channels are used to increase the power density in compact systems. Tuckerman et al. [8] first used mini channels in highly integrated electronics cooling systems and showed an increase in power density up to 790 W/cm$^2$ from an initial condition of 20 W/cm$^2$. In this work, it has been evaluated the feasibility of combining the mini channels into a system for the exploitation of thermal power by exhaust gases, in millimetric scales. Three different mini channel configurations have been selected and then numerically tested. The first one is a flat rectangular cross-section configuration, because in the work of Tuckerman this geometry has reported excellent results. The second one is a convergent configuration, because the Duryodhan's study [9] has shown how on micro size for bioengineering tests, it can break down thermal gradients through the combination of convection and conduction. The last is a branched fractal configuration, this network solution allows the reduction of thermal gradients in conditions of imposed thermal flux [10].

## 2. Method
The computational model has been developed utilizing the commercial code COMSOL Multiphysics, using CFD and heat transfer packages. In this model, chemical reaction and preheating of inlet gases are not considered, and the composition of inlet mixture and exhaust gases was neglected, i.e., gases have been simply considered as air. This assumption is based on the consideration that propane-air mixture is in a volumetric ratio of 1:25, and therefore it is in high excess of nitrogen which does not participate in chemical reaction.

The project consists of two computational models with two different inlet mass flow rates. The first model considers the overall combustion chamber and is aimed at its validation with experimental data (Figure 2). This model was run with the volume flow rate of the reagent mixture currently used to fuel the TEG, namely 3 Nl/min, which determines a mass flow rate of $1{\cdot}10^{-5}$ kg/s in each of the six chamber's walls ($D_h$=0,0019m), an input velocity of 0.5 m/s, and a Reynolds number of 64. The second model is used instead to compare mini channel configurations in the best-operating conditions achievable by TEG, i.e., using the input mass flow rate that optimizes the power transmitted to the thermoelectric modules. In this perspective, this model has been reduced to the study of a single wall to reduce computational time, after verifying the uniformity of the velocity field between the six walls with simulations of the overall combustor. The optimal mass flow inlet is equal to $1{,}9{\cdot}10^{-4}$ kg/s for each wall, with a Reynolds number of 1155 and an inlet velocity of 9m/s. This value is the result of an analytical model that combines the project targets to maximize the electrical power generated by the modules, by increasing the temperature difference $\Delta$T between the faces of the module itself.

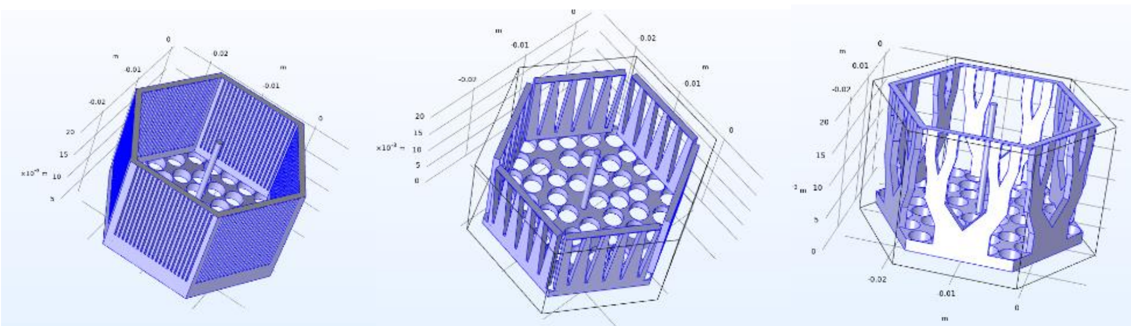

**Figure 2.** The fluid domain in COMSOL laminar simulations. From left to right: chamber with planar mini channels (configuration1), convergent mini channels (configuration 2), with fractal mini channel (configuration 3).

As the commercial TEMs can support up to 200°C of $\Delta$T whereas the other project constraints are:

- The air-propane mixture has an optimum catalysis temperature of 600 ° C, moreover, the mixture cannot be below 300 ° C, which allows the self-sustaining of the chemical reaction;
- The combustion must be stoichiometric, so the inlet mixture always has an air-propane ratio of 25:1 by volume;
- The need to have 600 ° C in the combustion chamber requires the use of 3D printing steel, which withstands temperatures up to 1400 ° C, but has a low thermal conductivity;
- The operating temperatures of the thermoelectric modules cannot exceed 300 °C;
- Hot gas current must have the most constant thermal profile possible during the passage through the channel-wall in a direction transversal to the thermal flow, since the thermal gradients on the gas side affect the faces of the TEM and reduce its performance;

with an increase in the total volumetric flow rate of the inlet mixture from 3 Nl/min to 27Nl/min, and with a bypass of air in a ratio of 1:1, the transmitted power has been increased from 1.7 to 8.4 W and has been supplied to each wall $1{,}9\cdot10^{-4}$ kg/s of mass flow inlet.

### *2.1. Model setup*

The geometric parameters chosen to build the mini channels are a compromise between the reduced size of the wall and the need to create as many mini channels as possible in the same section. To allow the comparison, the three configurations have been built with the same length and height of the cross-section. With these two parameters, 19 mini channels have been built with configuration 1 and an aspect ratio of 2.5. To create at least six converging channels, it was necessary to imprint an angle of inclination not greater than 2.95°, that provide an aspect ratio of 0.5 at outlet and 2.5 at inlet. However, for the fractal configuration that requires at least two bifurcations, a single mini channel has been inserted (aspect ratio of 0.667).

**Table 1.** Mini channels geometric parameters.

| | Configuration 1 | Configuration 2 | Configuration 3 |
|---|---|---|---|
| Base of cross-section | 0.4 mm | 0.4 mm | 0.4 mm |
| Height of cross-section | 1 mm | 1 mm | 1 mm |
| Length of mini channel | 18 mm | 18 mm | 18 m |
| Angle of inclination | - | 3° | 80° |
| Number of mini channels | 19 | 6 | 1 |

For the model of the whole combustor, a laminar study was chosen due to the low inlet velocity.
For the mini channel geometries comparison, given the high value of Re at the entrance region [11], a k-ε turbulence model has been used.
For the thermal analysis, a constant temperature condition has been set on the steel wall corresponding to the interface with thermoelectric modules. The mesh was performed with the default triangular and tetrahedral mesh algorithm available in COMSOL Multiphysics with a minimum mesh size of $6.5\cdot10^{-4}$ mm. The mesh consists of $8.5\cdot10^{5}$ elements, this choice is due to the results of a sensitivity analysis, conducted between $17\cdot10^{5}$ and $4.45\cdot10^{5}$ elements. Simulations were carried out with a multi-grid algebraic solver. The choice of this solver is dictated by the magnitude and complexity of the CFD model to be developed [12]. The solver works in a segregated way, i.e., first flow field is solved and then the temperature field is determined based on velocity results previously found.

Computational time has been about 1 hour and 20 minutes using four cores of 3.60 GHz. Simulations have been stopped when the continuity residual is lower than $1 \cdot 10^{-4}$.

### *2.2. Thermography analysis*

The model validation was carried out by comparing the results of the 3D simulation on the whole combustion chamber with the experimental data. The mass flow rate inlet of $6.275 \cdot 10^{-5}$ kg/s has been used, with a laminar solver. The experimental campaign has been conducted with the use of thermographic images of the side walls of the combustion chamber isolated from thermoelectric modules and exposed to stationary air. The FLIR Termovision A40 IR camera has been set to an emissivity value of 0.24 and used jointly with K-type thermal probes placed on the combustor surface and. Under these operating conditions, thermal profiles in transverse direction have been obtained for the four walls under analysis. All the four thermographs have a decreasing trend, in agreement with physics, as the temperature reduces linearly from the region in contact with the pellets how far the cap is sealed. The thermal gradient is 25°C for all the analyzed surfaces. Validation has been made by imposing a convective heat transfer coefficient of 22 W/m$^2$/K on all walls for the basic condition without mini channels. The model, in the same operating conditions, shows a thermal trend with a temperature drop of 25 ºC that agrees with the measurements, but the temperatures deviate from the measured values of 200 °C (Figure3). This is because the simulations do not consider all the phenomena that occur simultaneously within the combustion chamber, first the preheating of the entering mixture.

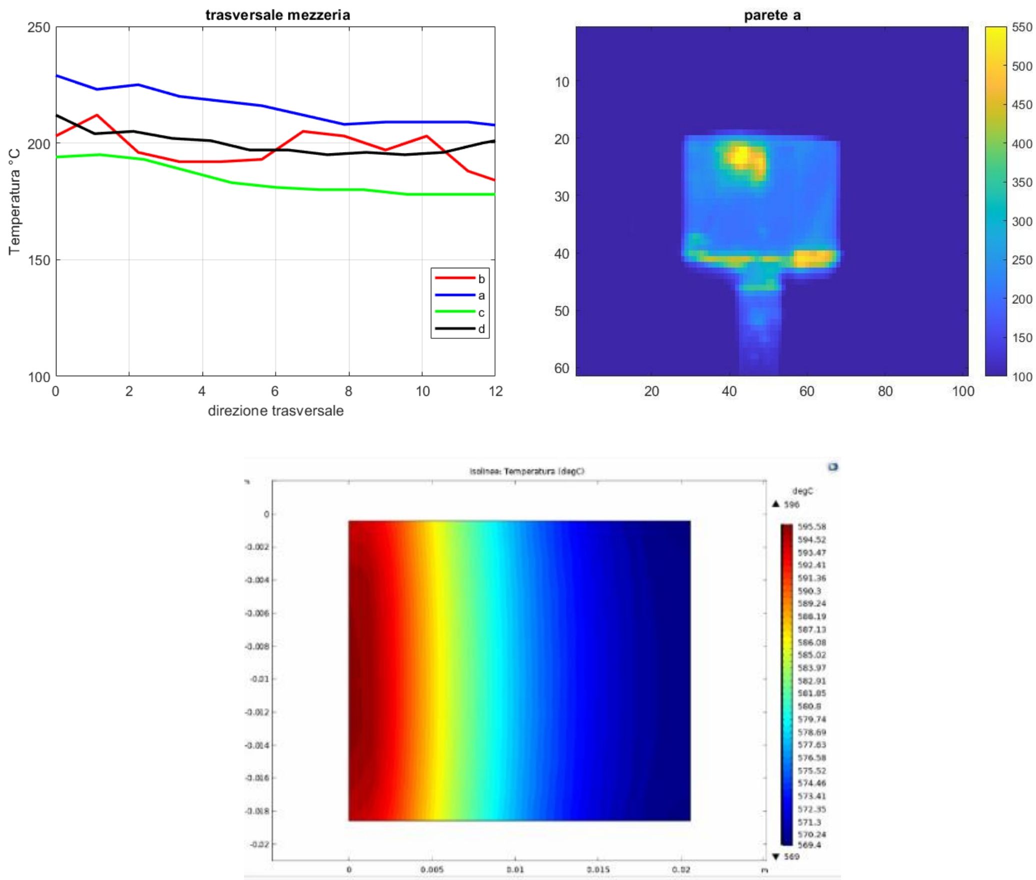


**Figure 3.** Temperature gradient from experimental data in four chamber's walls (left), IR image (right), the model results at the same operating conditions of the experimental data (bottom).

## 3. Results

The results, presented in Figure 4, show a section in the x-y plane of the mini channels, in the half of inlet section at z=0mm. All four cases are evaluated at system optimum inlet mass flow rate of $1{,}9\cdot10^{-4}$ kg/s and display the velocity field that is generated inside the mini channels beyond an entrance region of 8 mm length. The basic case highlights how, with an inlet velocity of 9 m/s in the outlet section with a flat duct, it's possible to achieve local velocities no higher than 11m/s. For configuration 1, the velocity profile accelerates in all 19 mini channels, in a uniform trend, up to reach a velocity of 38 m/s in the exit section, i.e., with an increase of 300% with respect to the base case. In configuration 2, convergent channels allow to overcome the results of the straight mini channels achieving local velocities in the outlet section of 75.8 m/s. Configuration 3, with network geometry, attains slightly higher velocities at the outlet of the mini straight mini channels, due to the regions following the bifurcations of the fluid and the fact that all the input mass flow rate is conveyed in a single channel.

Regarding pressure drop, Table 2 shows $\Delta P$ for each configuration across inlet and outlet sections. It is evident that the convergent configuration is the one with maximum pressure drop, followed by configuration 1, and then by configuration 3. For heat transfer analysis, the same boundary conditions have been applied to be able to compare the 3 cases. Precisely a wall temperature of 200 ºC has been set, to assess the bulk temperature at the fluid outlet sections having imposed an inlet temperature of 20 ºC. Numerical results display that the 19-mini channels can heat the gas more effectively, with a temperature increase of 52% compared to the case without mini channels. The converged configuration stops at a 27%, while for the network configuration is the one with less increase in temperature (only 15%). These results highlight that even if the configuration 1 is not where the fluid flow has the maximum velocity, the 19 mini channels solution is the best from the heat transfer point of view. This is due to the fact that the exchange areas between fluid and solid increases as the number of mini channels.

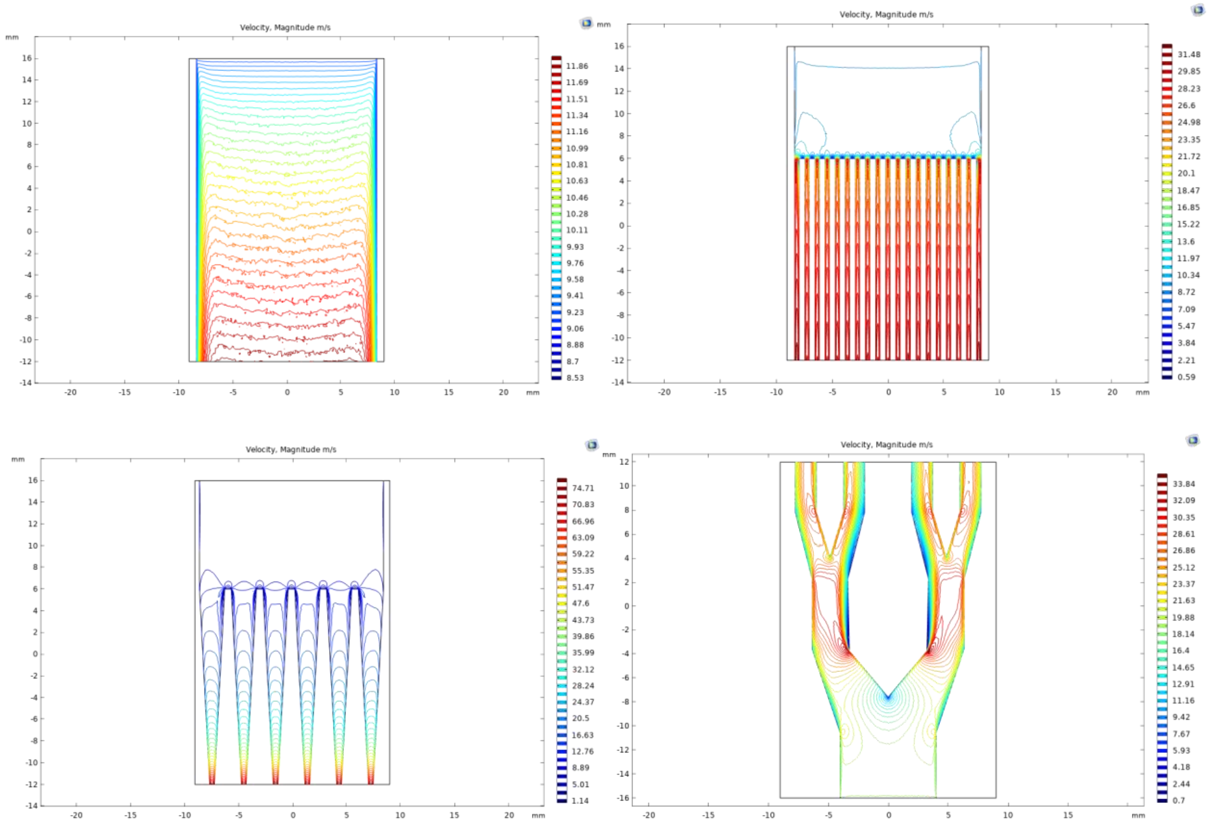


**Figure 4.** Velocity field contours for the base case and the three mini channels configurations at the same inlet velocity of 9m/s and external wall temperature of 200°C.

**Table 2.** Pressure drops and outlet bulk temperature results of the computational models.

| | $\Delta$P [Pa] | $T_{bulk\_outlet}$[°C] |
|---|---|---|
| Base case | 71 | 99 |
| Configuration 1 | 1146 | 151 |
| Configuration 2 | 3020 | 125 |
| Configuration 3 | 790 | 114 |

## 4. Conclusion

It has been analysed how it is possible to increase heat transfer between a mini catalytic combustor and a thermoelectric module, using mini channel solutions. The three configurations chosen for the computational simulations show promising results, regarding heat transfer enhancement. Configuration 1, with 19 rectangular section straight mini channels is the best compromise between heat transfer enhancement and pressure drops penalization. In view of new measurements, in force of the promising modelling results, the three mini channels configurations have been printed in SS316L with Selective Laser Melting technique (Figure 5). The design of the combustion chambers is a trade-off between technological feasibility and best numerical results.

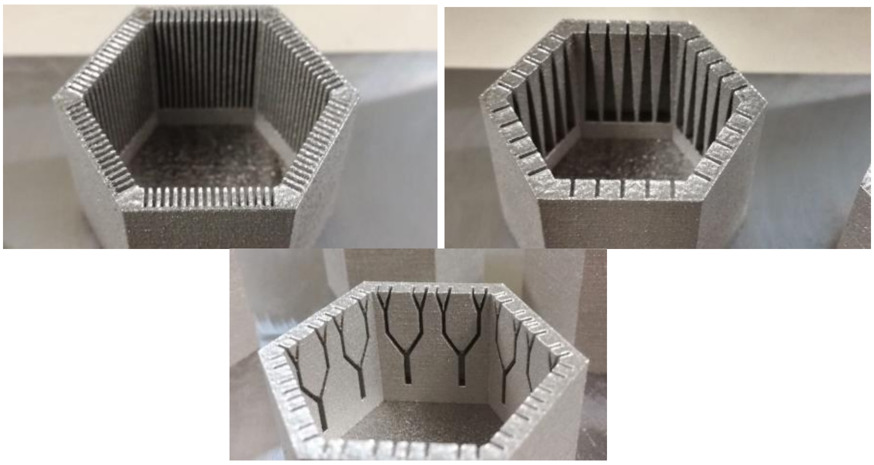

**Figure 5.** New combustion chamber prototypes with different mini channels configurations.

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