

# New Metamaterials with Combined Subnano - and Mesoscale Topology for High-efficiency Catalytic Combustion Chambers of Innovative Gas Turbine Engines

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**Abstract:** The object of the study is a catalytic combustion chamber that provides a highly efficient combustion process through the use of effects: heat recovery from combustion, microvortex heat transfer, catalytic reaction and acoustic resonance. High efficiency is provided by a complex of related technologies: technologies for combustion products heat transfer (recuperation) to initial mixture, catalytic processes technology, technology for calculating effective combustion processes based on microvortex matrices, technology for designing metamaterials structures and technology for obtaining the required topology product by laser fusion of metal powder compositions. The mesoscale level structure provides combustion process with the use of a microvortex effect with a high intensity of heat and mass transfer. High surface area (extremely high area-to-volume ratio) created due to nanoscale periodic structure and ensures catalytic reactions efficiency. Produced metamaterial is the first multiscale product of new concept which due to combination of different scale level periodic topologies provides qualitatively new set of product properties. This research is aimed at solving simultaneously two global problems of the present: ensure environmental safety of transport systems and power industry, as well as the economy and rational use of energy resources, providing humanity with energy now and in the foreseeable future.

## 1. Introduction

The modern fleet of engines, including gas turbines, are various designs of thermal machines that use the kinetic and potential energy of the working body, which is a heated up to high temperature gas mixture of combustion products and the volume of air passing through the engine. For the next 30-50 years, there is no other alternative for heat engines, especially in the field of aviation equipment and ground-based power gas-turbine installation.

The combustion chamber, in which the fuel combustion process is carried out, is an indispensable part of these engines. The thermal effect of combustion depends from how efficient the combustion process will be, i.e. how effective the hydrocarbons oxidation in the fuel-air mixture stream will be. More complete combustion of fuel provides not only high thermal efficiency, but also reduces the release of harmful combustion products (CO and NO<sub>x</sub>) into environment.



Macroscale combustion process correctly organized in the combustion chamber ensures the uniformity of the gas flow temperature front at the exit of the combustion chamber and significantly increases the efficiency of the all engine.

Topology optimization has been recognized as one of the most effective design tools with the least mass and performance, especially in aeronautical and aerospace engineering [1].

Most of the existing research on topology optimization focuses on the design of mono-scale structures. In other words, the structures under consideration are made of homogeneous materials. In recent years, heterogeneous and metamaterials with increased specific mechanical and other performance characteristics, such as fibrous composite, structured porous metal, have been increasingly used. Despite the complex topology of such materials of micro and submicro levels, from the point of view of structural analysis these materials can be considered as homogeneous and traditional approaches to design are conventionally applied to them.

At the same time, the optimization of multiscale structural topology has a significant impact on their properties. Therefore, for calculation of effective mechanical designs, its microscopic heterogeneity is taken into account for an accurate estimation of structural indicators. In this connection, there is a need to design a topology of materials of both scale levels - a macroscopic structure and a microscopic structure simultaneously. Simultaneous optimization design of both the structure and the topology of materials at the macro level can be found in the early works [2,3]. Modern multi-scale analysis is outlined in work [4]. The traditional approaches to combustion processes optimizing in combustion chambers of known designs have practically exhausted their effectiveness. In particular, the use of modern software for finite element modeling of gas-dynamic flows in combustion chambers allows optimizing the temperature front and increasing the completeness of combustion, but they do not solve the fundamental problem of creating an environmentally safe combustion chamber. New approaches for chamber design needed for the combustion processes intensification.

As a material with a combined subnano - and mesoscale topology, in the context of this project we mean a metamaterial that has a periodic structure at each level. The structure of the mesoscale level provides the combustion process with the use of a microvortex effect with a high intensity of heat and mass transfer. High surface area (extremely high area-to-volume ratio) created due to nanoscale periodic structure and ensures catalytic reactions efficiency. Such metamaterial will be the first multiscale product of new concept which due to combination of different scale level periodic topologies provides qualitatively new set of product properties.

Thus, the object of research is related to the following critical areas and technologies:

- metals and alloys with special properties;
- technologies for creating membranes and catalytic systems;
- technologies for creating energy-efficient engines and propulsors for transport systems.

The subject of scientific research are:

- experimental research and modeling of combustion processes using microvortical matrices realized with the help of geometry of periodic structure;
- experimental studies of the surfaces catalytic activity produced by 3D printing and by thermal coating of catalysts deposited on developed surfaces;
- designing the topology of structures that realize the microvortical effect by computer simulation methods;
- development of technology for production of metamaterial by Selective Laser Sintering (SLS);
- development of a digital metamaterial model and experimental verification of the model;
- development of technical solutions prototypes for the design of the combustion chamber;
- development of technological solutions prototypes for growing a combustor by the SLS method from metal powder materials;
- development of technological solutions for the thermal spraying of catalytically active coatings.

In the context of the methods outlined above, it should be emphasized that the development of combustion chambers with intensification of the combustion process will permit to burn heavy

hydrocarbons fuels (product of recycled biowaste conversion) optimally. Such combustion chambers will be possible to include in the structure of power installation operating on recycled wastes of biological origin.

Development of innovative microvortex combustion chambers designs oriented to the use of metamaterials with a multiscale topology will allow to carry out combustion processes of low-grade hydrocarbon fuels with low-emission pollutants (CO and NO<sub>x</sub> emissions will be less than 5 ppm). Low emission of pollutants is provided due to high completeness of combustion. The thermal efficiency of combustion will be more than 99%.

Development of technologies for creating metamaterials with a multiscale topology of submicro and meso levels using selective laser alloying of metal powder compositions will ensure creation of the material by a 3Dx2 topology level technique. Each scale level of metamaterial regular topological structure provides specific functional properties. In sum, such material provides a complex of properties, which has a cumulative character, superior to the simple addition of effects taken separately.

As a result of the project, the following local objectives will be achieved:

- providing scientific and research organizations with new and effective methods and tools for conducting research of the combustion processes analysis under conditions of its intensification with the help of a microvortex effect, catalytic reaction and acoustic resonance;
- obtaining significant scientific results allowing to proceed new types of catalytic vortex combustion chambers production;
- mastering of new methods, principles of metamaterials creation with 3Dx2 multiscale level topology, allowing to achieve significant results in the future at serial production by SLS method.

Thus, the global goal is to bring new scientific and technical products to the market, develop world-class technologies for the design and manufacture of a new generation of high-efficiency, catalytic vortex combustion chambers from metamaterials with a multiscale topology of the 3Dx2 level. Such products will reduce the environmental burden on nature through the optimization of combustion processes. The research aimed at organizing the optimal combustion cycle in the combustion chamber, the design and specially developed metamaterial from which it is manufactured, which together provide the multilevel intensification of the combustion process. This research is relevant, it is aimed at solving simultaneously two global problems of the present: ensure environmental safety of transport systems and power industry, as well as the economy and rational use of energy resources, providing humanity with fuel and energy now and in the foreseeable future.

## 2. Experimental

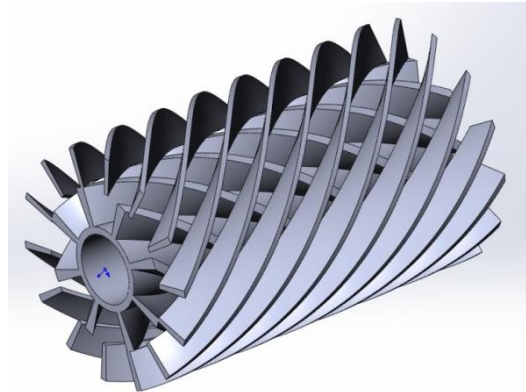
The microvortex catalytic combustion chamber produced by a 3D printing method by direct computer modelling. Further the model under the set program is divided into layers of the certain thickness. An operating computer of 3D printer received information about each layer and regulates sintering according program until complete construction of article. For 3D printing the metal powder of stainless steel 316L was used with the particles (spherical form) size up to 50 microns, with density of a powder 4, 74 g/cm<sup>3</sup>.

Construction of a product realized on installation SLM 280 with the construction chamber 280x280x350 mm. As an energy source used the infra-red fiber laser (a source of electromagnetic radiation), by length of a wave of radiation 1075 nanometers, capacity 400 W with a cross-section direction of a laser beam distribution. This installation gives possibility of complex research for optimization of products selective laser synthesis parameters. Products were built in nitrogen atmosphere in the working chamber which is filled with protective gas before construction. The platform, on which the articles were synthesized, was warmed up to 150°C. [5].

## 3. Results and discussion

In the proposed project for the implementation of the combustion processes intensification, the microvortex catalytic combustion chamber is realized as a design of a two-level multi-scale metamaterial.

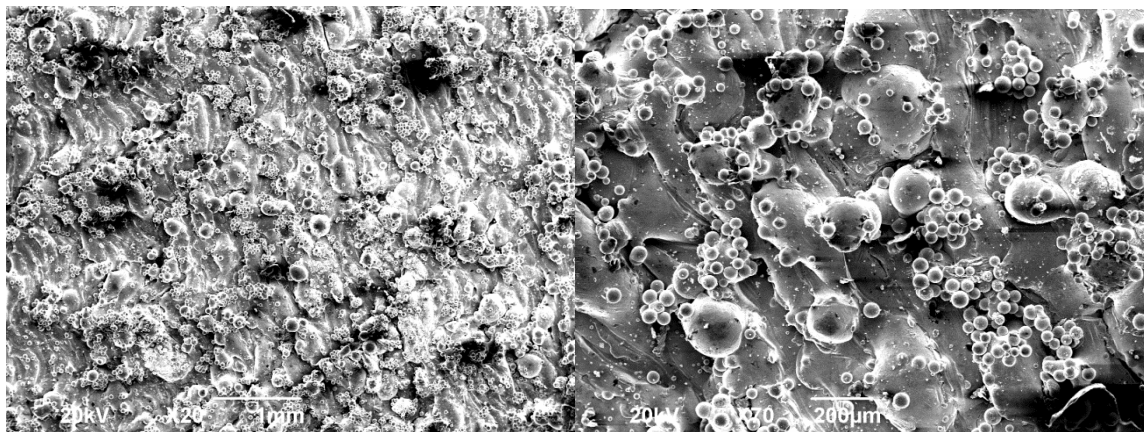
At the meso level, the combustion chamber is a metamaterial realized in the form of concentrically arranged annular structures shown in figure 1.



**Figure 1.** Model of the microvortical combustion chamber.

Each structure is formed by a family of helical ribs equally distributed around the circumference of the perimeter, the working surfaces are spirally along the generatrix of the cylinder. The direction of twisting of the spirals of two adjacent concentric structures is opposite, respectively, right and left.

Figure 2 shows a SEM microphoto of the finned working surface prepared for catalytic coating application.



**Figure 2.** SEM microphoto of the finned surface for catalytic coating application.

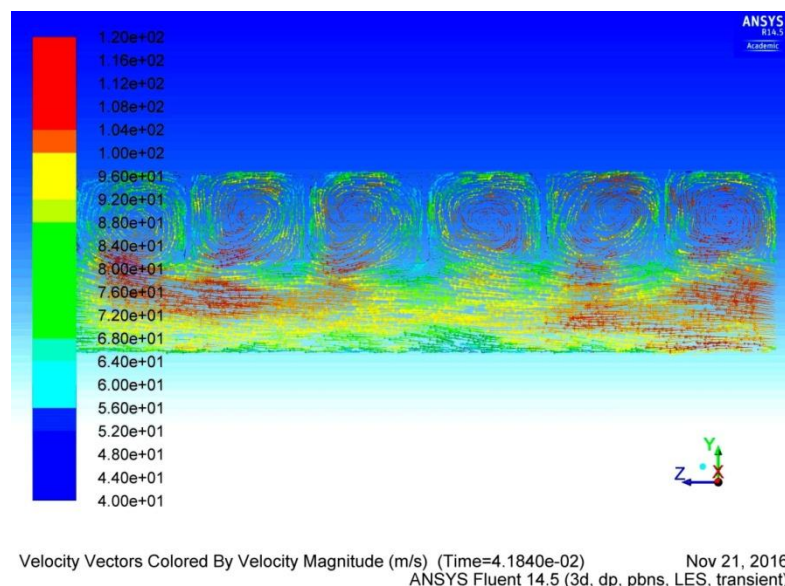
Metamaterial is, first of all, a material whose properties are due not so much to the properties of the constituent elements as to the artificially created periodic structure [6]. The topology of the combustion chamber at the mesolevels perfectly suits this definition, it has a periodic structure which propagate in two directions - along the axis and radially, and its functional properties are determined mainly by its topology. The preparation of the ribs surface for the catalytic coating provides a multiple increase in the surface area.

During combustion, the gas mixture moves along the helical channels between the ribs, and a micro vortex matrix is formed at the point where two coplanar flows of the gas mixture which move along



the two adjacent structures meet. Periodically located in the meeting places, microvortical matrices provide an intensification of the combustion processes due to the vortex effect.

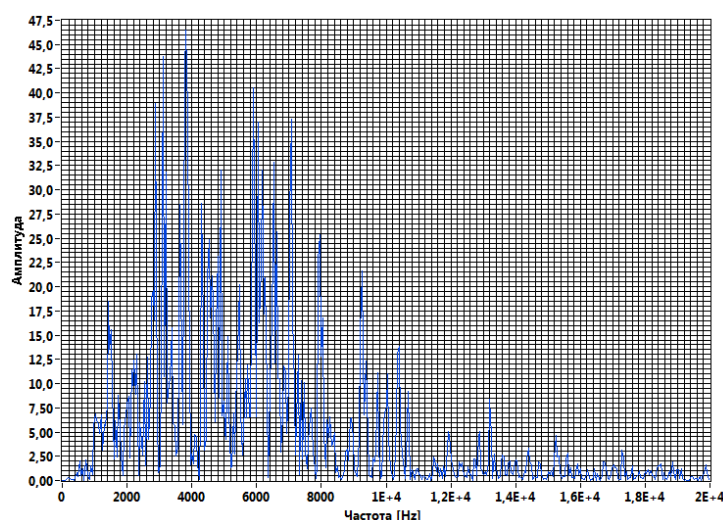
Figure 3 presents the results of numerical simulation of the process of a linear vortex interaction intersecting transversely located cells through which conjugate flows occur.



**Figure 3.** Results of numerical simulation of the process of a linear vortex interaction.

Interaction of intersecting streams generates a system of micro-vortex structures in which the level of mass forces generated by the twisting of flows is many hundreds and thousands of  $g$ , where  $g$  is the acceleration of gravity. As a result of centripetal accelerations, the mixture of combustion products on the catalytic surface having the highest temperature (and the lowest density), quickly float to the centers of the vortices and are carried downstream to the exit from the combustion chamber.

Fig. 4 shows the amplitude-frequency characteristic of pressure pulsations in the center of the microvortex cell.

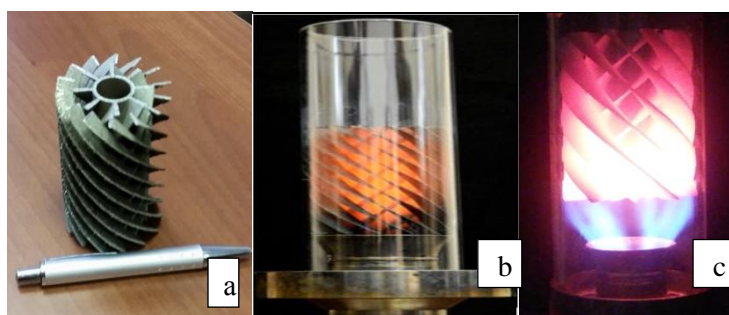


**Figure 4.** Amplitude-frequency characteristic of pressure pulsations in the center of the microvortex cell.

Local pressure pulsations form the parameters of acoustic emission as a whole in the micro vortex combustion chamber and contribute to the integration of heat exchange and combustion processes.

One of the main difficulties in implementing such a design is the technology. The screw structures of the metamaterial at the meso level form a spatial grid, which is an inseparable connection that is unsuitable for manufacturing by machining technologies. From the technological point of view a rational way of making such design is a new additive technology-selective laser sintering (SLS) of metal powder compositions.

Another way of intensifying combustion processes and ensuring high completeness of the oxidation reaction is provided in the work- a catalytic reaction on the surface of the catalyst fins. A certain experience of using the catalytic effect with respect to the combustion processes of hydrocarbon fuels is set forth in works [7,8]. For the first time in the world were designed and printed in 3D technique catalysts on the base of steel powder (figure 5a) and Ni-Al alloys.



**Figure 5** a) Catalyst 3D (from steel) block with intricate configuration and coplanar channels, b) propane-butane and (c) methane combustion in 3D microvortical combustion chamber.

Heat- transfer paths with intricate configuration and coplanar channels of the flow pass section for heat transfer enhancement and extending of heat transfer surface were produced (fig.5a). As a result of the gas-dynamic research proposed a fundamentally new way of organizing the catalytic oxidation in combination with combustion in the gas phase. The technology is put in heat-known scheme of coplanar channels, which provides high rates of heat transfer. 3D printed blocks were used as catalysts for methane oxidation, CO oxidation and methane combustion processes (fig.5). High flow rate of the working body - more than of 60 -100 kg / s, and respectively flow rate 30-70 m/s reduces the effectiveness of the known technical solutions to unsatisfactory hydraulic losses values. In the center of the gas-dynamic research proposed a fundamentally new way of organizing the catalytic oxidation in combination with combustion in the gas phase.

The activity of catalysts in heterogeneous catalysis strongly depends on the size and state of their surface, so the method of the catalyst manufacturing is important. With respect to the present design, the surfaces of the helical ribs of the catalytic combustion chamber along which the gas mixture moves is the catalyst surface or surface which can be coated by catalyst.

In the case of microvortex chambers, an increase in the area of the catalyst can be achieved by using the properties of a metamaterial with a topology of submicroscopic dimension. This is the second level of the metamaterial structure for the combustion chamber. To grow the combustion chamber by the SLS method, it is suggested to use powders with the size of the fraction up to 60 microns, which makes it possible to obtain periodic structures of microcells (surface roughness substructure with a regular profile of protrusions and valleys) on the working surface of the ribs due to the use of special technological methods. This will allow multiplying the active area of the catalytic reaction.

As a result, the developed metamaterial for the vortex catalytic combustion chamber has a two-level multiscale topology. Each of the two described levels of metamaterials carries its own functional

load. A cumulative effect is achieved on the intensification of combustion processes, which by efficiency exceeds the sum of the positive effects of each scale level taken separately.

#### 4. Conclusion

The new catalytic combustion chamber that provides a highly efficient combustion process through the use of effects: heat recovery of combustion products, microvortex heat transfer, catalytic reaction and acoustic resonance is developed.

Such material is the first product of multiscale metamaterials new concept which due to a combination of periodic topologies on different scale level provides qualitatively new set of product properties.

#### Acknowledgments

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