MICRO RING-ENGINE NUMERICAL FLUID DYNAMICS ANALYSIS

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Abstract: This paper presents an idea and preliminary results of numerical CFD simulations of the proposed ring-engine construction dedicated for air propulsion or generation of electric power. An atypical fuel (hydrogen peroxide) is used in the analyzed construction. The proposed ring-engine has compression-decompression chambers forming a part of a ring periodically filled by cooling air and hydrogen peroxide vapor. The H_2O_2 is decomposed in exothermic reaction increasing pressure inside the chamber. High pressure gas contents of the compression-decompression chamber is periodically decompressed by the jet nozzle generating torque. The paper contains the description of the ring-engine idea, the schematic engine geometry and a set of data visualizing pressure, velocity, temperature and species distribution inside the engine components.
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Key words: hydrogen peroxide, sequential cross-flow idea

1. INTRODUCTION

The development of micro air vehicles (MAVs) generated the need to have small engines with characteristics satisfying operating requirements. One of them is the efficient power generation in a longer time at steady engine rotational speed (cruising conditions) [1].

Adoption of a hydrogen peroxide as a fuel in microscale engine was biologically-inspired by a defence mechanism of an insect - a bombardier beetle [2].The insect forms a noxious spray by reacting small amounts of hydroquinone with hydrogen peroxide in the presence of the catalysts catalase and peroxidase in a pair of small (2 mm size) combustion chambers placed in its abdomen. This exothermic reaction produces water and heats it above boiling point. The resulting steam is ejected to strike an enemy. The beetle does this at 400 to 500 cycles/s. Such example of successful hydrogen peroxide decomposition in micro scale ensures its repetition in technical application. Due to that such atypical fuel is used in analyzed micro engine construction. Hydrogen peroxide has been reconsidered as a promising green fuel [3]. It also has several other unique features of the monopropellant such as temperature control, safety, ease of use, non-toxicity and low combustion temperatures. The main advantage of the hydrogen peroxide is stability at ambient pressure in a wide range of temperatures but rapid, exotermical decomposition into water (steam) and oxygen in presence of catalyst materials or high temperature igniters [4]. This gives an easy and exact control of use of this fuel in micro scale as well as clean and environment friendly output of hot gases. H_2O_2 is stored as a liquid, requires to be heated to the saturation point (423 K) and than delivered as a vapor to the reaction chamber. At concentration of 90% H_2O_2 is already available commercially and ensures complete decomposition at temperature about 1022 K. Such temperature level of gas products of decomposition is acceptable in silicon wafer technology, which is great advantage of proposed fuel.

Such a monopropellant like H_2O_2 can be used in a simpler way in an engine utilizing principle of the Heron turbine. Propellant can be burned or decomposed in steady flow combustion chamber and than delivered at high pressure to rotating nozzles generating torque. However, the proposed engine was intended to freely aspirate oxidizer and fuel and perform a chemical reaction in a closed volume (reaction chamber). H_2O_2 is used only as an exemplary fuel.

2. RING ENGINE IDEA

Any heat engine had to go through four phases of operation. The first phase is filling the reaction chamber by the fuel and oxidizer. The second phase is chemical burning of fuel accompanied by the increase of pressure. The third one is expansion of high pressure and high temperature gases. The fourth phase consists of gases exhaust.

In Fig. 1 a possible technical realization of a micro engine of 10 mm rotor diameter is presented. A set of reaction chambers constitute the main part of the ring engine. They have a form of channels with length about 10 times longer than the channel width. In each of them four phases of operation had to be realized sequentially. In Fig. 2 the considered phases of operation in a single reaction chamber were depicted.

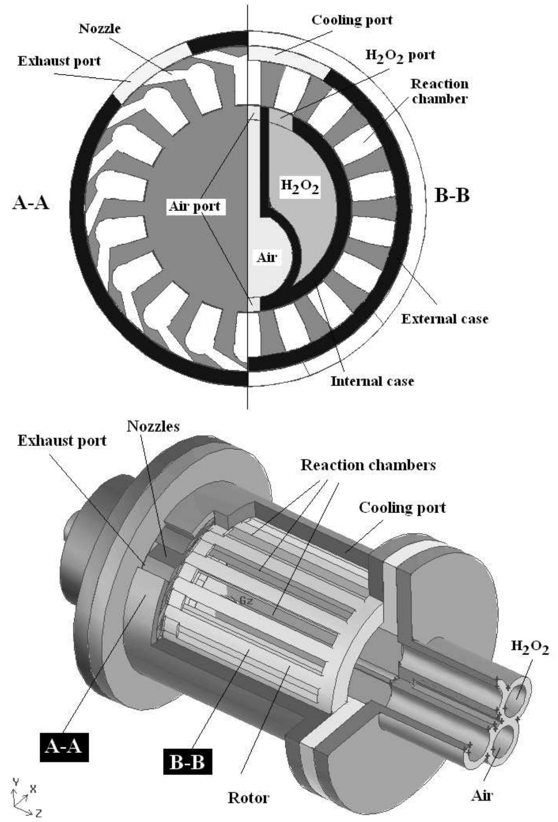

Fig.1: Possible micro engine construction

Chemical reaction between fuel and oxidizer takes place with a limited velocity. In this specific reaction chamber geometry the time of full decomposition of H_2O_2 depends on the one hand on the reaction surface propagation speed and on the other hand on the ignition point position. To reduce the process time, ignition should be realized in the middle of the channel length. Reaction surface propagation speed depends on the turbulence level which is influencing the mixing process. Simple rectangular obstacles on the reaction chamber walls have been proposed as micro vortex generators increasing the turbulence level (see Fig. 3). The expansion process (phase c in Fig. 2) is limited by the chock flow conditions at the nozzle. In general the process time is short. Due to the gas inertia after the expansion small underpressure is generated inside the reaction chamber. The gas velocity at the nozzle is high but in the chamber it is relatively low. Due to the high length of the reaction chamber its cleaning from the exhaust gases and filling by the fuel/oxidizer mixture in the chamber main axis direction is rather difficult and time consuming.

In the proposed ring engine construction an idea of a sequential cross-flow has been applied. Such name was given due to two main flow directions realized sequentially

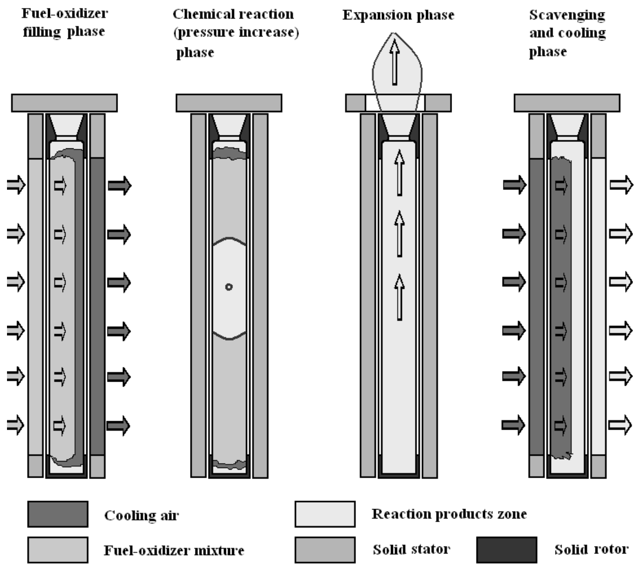

Fig. 2: Four phases of single reaction chamber operation.

in the reaction chamber. The outflow of the compressed hot gases is realized along main reaction chamber axis (phase c in Fig. 2). But the scavenging and filling the chamber by the fuel and oxidizer is realized in direction perpendicular to the main chamber axis (phase d and a in Fig.2). In that way the sequential cross-flow scheme is realized. The path of the fuel motion is very short and even realized with low velocity takes very little time. The hot reaction chamber should be periodically cooled and fresh mixture of fuel and oxidizer should be separated by the neutral medium from the hot exhaust gas. Because of that the use of ambient air as a cooling and separating medium has been proposed. After expansion of hot exhaust gas, pressure in reaction chamber drops below the ambient pressure. Such pressure difference can be used for the air aspiration. Inflow velocity in such conditions is rather low. After a while the opposite side of the chamber can be opened and the chamber can be connected with the atmosphere (phase d in Fig. 2). Propellant mixture can be delivered at pressure higher than ambient so that the mixture delivery can be realized at higher velocity (phase a in Fig.2).

The operating cycle starts from configuration seen at sketch a) in Fig.2. Both longer sides of the combustion chamber are opened. There is a cross flow of the mixture through the reaction chamber. When the mixture reaches the chamber right side this side is closed. After a while the left side is closed. Now reaction chamber contains the mixture of the cooling air and the fuel (b in Fig.2). Then fuel is ignited. The burning process progresses to ends of the reaction chamber along it's main axis. After the end of the burning (decomposition) process, nozzle at one of the shorts ends opens and the expansion process starts (c in Fig. 2). Reaction of expanding gas at the nozzle generates torque. Speed of reacting front propagation strongly depends on the turbulence level. When the expansion process draws to the end, pressure inside the reaction chamber lowers below the ambient pressure and the left side of the chamber can be opened for cooling air delivery. Layer of neutral cold air is used for separation of fresh fuel from the hot exhausted gas (d in Fig. 2). After a while the fuel is delivered from the left side pushing the separating air layer to the right (a in Fig. 2). When the exhaust gas is removed from the reaction chamber the right side of the chamber is closed. Details of this process are shown in Fig. 5 and Fig. 6.

3. NUMERICAL SIMULATION

All simulations were performed with FLUENT program. Simulation of chemical reaction dynamics is based on a turbulence-chemistry interaction model. Decomposition of the H_2O_2 was modeled as a single reaction process with pre-exponential constant equal 1.0e13 and activation energy 1.8e8 (J/Kg/mol). Reaction of finite rate/eddy dissipation type was used with mixing rate coefficient A=4 and B=0.5. Such reaction model can be used under assumption that turbulent flows exist, which is valid in a considered case. Both the Arrhenius rate and the mixing rate are computed and the smaller of the two is used. The turbulence relatively slowly convects and mixes cold reactants and hot products into the reaction zones, where reaction occurs rapidly. In such cases, the combustion is limited by the mixing process. The chemical reaction rate is governed by the large-eddy mixing time scale, k/ε . Due to that the $k-\varepsilon$ turbulence model was applied. However, an ignition source is not required to initiate combustion but in considered case the small area inside the reaction chamber was heated in a short time to initiate the decomposition process. Technically ignition can be realized by the short burst of the laser beam.
Once the flame is ignited, the eddy-dissipation rate is generally smaller than the Arrhenius rate, and reactions are mixing-limited. It has been observed that the reaction front propagation speed is about 10 m/s. Due to the relatively slow propagation of reaction front the ignition area was located in the center of the reaction chamber to reduce it's total time. To speed up the decomposition process in a small channel, vortex generators have been applied (see Fig.3).

The main part of the micro engine is a rotor containing walls separating reaction chambers. Internal and external sides of chambers are closed by the cylindrical walls of the casing (see Fig.1). Cooling air and fuel are delivered by slits in the internal cylindrical case. Cooling air is removed through the openings in the cylindrical external case. One end of each chamber is connected with a obliquely located jet nozzles generating torque. Disk parts of the casing contains the bearings and air fuel pipes.
A disk version of the ring engine was also considered.

4. RESULTS OF CALCULATION

Simulations of simplified 2D versions of a single reaction chamber with sequentially changed boundary conditions simulating all phases of operation have been made. The decomposition process was simulated in the 2D chamber cross section along the main axis (see Fig. 3 and Fig. 4).

Fig. 3: Concentration of hydrogen peroxide: a) after filling process, b) just after ignition, c) during decomposition, d) just before the full decomposition

Fig. 3 depicts the concentration of hydrogen peroxide inside the reaction chamber at different phases of cycle. Additionally, except two reaction fronts generated by the igniter, existence of a third front started at the contact area with the hot rest decomposition products from the previous cycle of operation.
Three characteristic velocity patterns inside the reaction chamber are presented in Fig.4. During decomposition phase only local areas of the fluid motion exist near the decomposition front and in vortex generator vicinity. At expansion phase highest velocity (600 m/s) exists at the nozzle and much smaller inside the chamber. During filling phase strong cross flow in the chamber is generated.

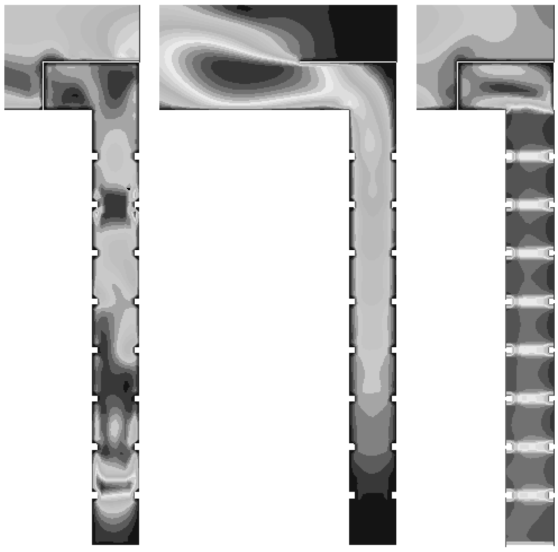

Fig. 4: Velocity magnitude distribution at decomposition phase, expansion phase and filling phase.

Process of cooling and fuel filling was analyzed in a plane perpendicular to the main axis (see Fig. 5 and Fig. 6).

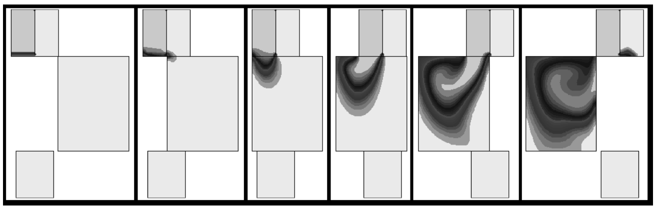

Fig. 5: Concentration of the hydrogen peroxide in chamber cross- section during the cooling and filling phase.

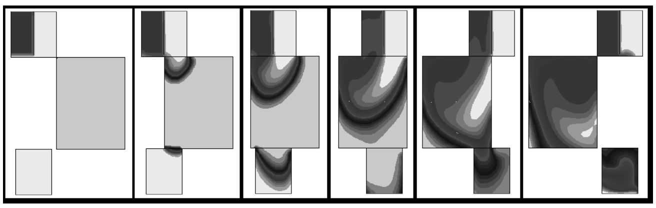

Fig. 6: Gas temperature in chamber cross-section during the cooling and filling phase.

The top right channel shown in Fig 5 and 6 contains air at temperature 300 K and the top left channel is filled by hydrogen peroxide at temperature 423 K. Comparing simultaneously frames in Fig. 5 and Fig. 6 process of cooling and fuel filling can be analyzed.

Building up of the pressure inside the reaction chamber was shown in fig. 7.

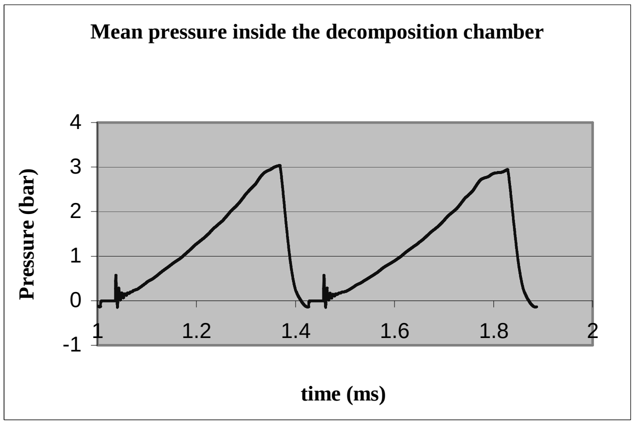

Fig. 7: Variation of the reaction chamber pressure in two cycles.

The time of H_2O_2 decomposition is the dominating time in the cycle. Thanks to the cross flow idea cooling, cleaning and filling of the reaction chamber with fuel takes only 20% of the working cycle time. Micro engine (10 mm rotor diameter) can generate 9 W of mechanical power rotating at 75 000 rpm.

Conclusions

The presented ring engine idea contains one breaking innovation in wave engines construction. It is the application of the cross flow inside the combustion chamber in order to reduce the cooling and filling with fuel times. In that way the wave processes became less important and critical than in the classic construction. Proposed idea of the cross flow can be realized in macro scale at periodic combustion chamber gaining pressure and in that manner reducing the number of compressor stages required to realize the expected turbo engine pressure ratio.

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