Micro Engine Combustion Numerical Fluid Dynamics Analysis

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Abstract

This paper presents an idea and results of 2D and 3D numerical CFD simulations of the combustion process inside micro-engine construction dedicated for air propulsion. The engine is designed as the simplest construction realizing the idea of a constant volume combustion principle. An atypical fuels, hydrogen peroxide and hydrogen, are used. The H_2O_2 is decomposed in exothermic reaction increasing pressure inside the chamber of constant volume. The free oxygen being the result of decomposition process is then used to afterburn injected hydrogen. The high pressure water steam content of the reaction chambers is periodically decompressed by the jet nozzles, generating torque. The paper describes the micro-engine idea, and discusses results of numerical simulations of combustion and flows that visualize pressure, velocity, temperature, and species distributions inside the engine components.

1. Introduction

The development of micro air vehicles (MAVs) generated the need for small engines efficiently generating power over a longer period at steady engine rotational speed (cruising conditions). Micro-gas turbine engines [2], microrockets , micro-rotary internal combustion engines can be used for such purposes. Dramatic reduction of efficiency of micro devices have been observed compared to their macro-scale counterparts [2]. Due to that, new engine ideas, more suitable for micro-scale, had to be considered [3]. Adoption of a hydrogen peroxide as a pilot fuel in a micro-scale engine was biologically-inspired by a defence mechanism of an insect - the bombardier beetle [1]. 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 (see Fig.1). 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. Therefore, such atypical fuel can be used in analyzed micro engine. Unsteady combustion of a hydrogen in micro conditions seems to be the difficult task. The idea was to use the hydrogen peroxide decomposition as a piloting and stabilizing process for further combustion of hydrogen in presence of oxygen being the result of decomposition process. Stable hydrogen peroxide decomposition process stabilizes temperature on a level, which guarantee a non-quenching hydrogen-oxygen chemical reaction. 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 activated by high temperature igniters . 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. At concentration of 90% H_2O_2 is already available commercially.

2. Internal Combustion vs External Combustion

Comparison between a typical turbo engine cycle described by points 1-2-3-4 in T-S diagram, a wave engine (points 1-2-3'-4') and an micro engine with pulsating combustion chamber (points 1-2'-3'') is shown in Fig. 2.

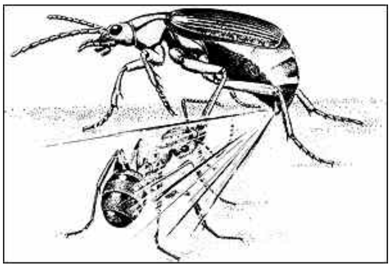

Fig. 1 Bombardier beetle in defence action – inspiration of micro fuel combustion choice

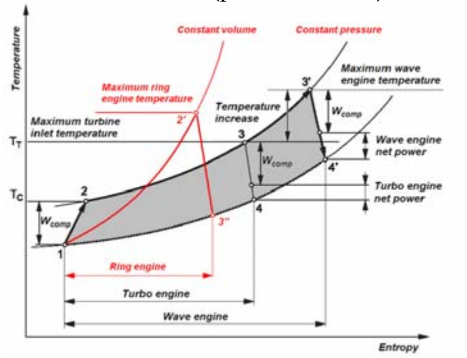

Fig. 2 Comparison of thermodynamic cycles of engines with classical chamber at constant pressure and engines using pulsating engine combustion chambers at constant volume.

The wave engine [3] is characterised by higher operating temperatures, higher power and higher efficiency in comparison with a classical turbo engine [2] especially in micro scale. An engine with pulsating combustion chamber guaranties higher efficiency and relative simplicity. The aim of the presented work was the combustion process analysis demonstrating features characteristic to the engine with pulsating combustion chamber. Characteristic for such engine is a combustion process realized at constant volume. The proposed engine was intended to freely aspirate oxidizer and fuel and perform a chemical reaction in a closed volume (reaction chamber) starting from ambient conditions.

3. Fuels

The behavior of combustion in small scale is different from large-scale combustion phenomena mainly due to increased heat losses and reduced residence time caused by small device dimensions. In small-scale devices heat loss rate is a significant factor frequently resulting in difficulties in flame stabilization and provoking flame quenching. Use of hydrogen peroxide as a pilot fuel in micro-scale seems to be reasonable choice due to existing biological examples confirming stable decomposition of this fuel in millimeter scale [1]. For concentrations above 63-64% H_2O_2 accelerated decomposition becomes self-sustaining. The oxygen is one of the products of the hydrogen peroxide decomposition. The free oxygen is used to burn additional fuel (hydrogen) in a afterburner using the hydrogen peroxide decomposition process as flame stabilizer. Generally two fuels are used. The first one, a pilot fuel it is a hydrogen peroxide. The second one it is a hydrogen. Pilot fuel is used for preparation of the stable combustion conditions for the second fuel.

4. Micro Engine Construction

A possible technical realization of a micro engine of 10 mm rotor diameter is presented in 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. Cooling medium (water steam) and pilot fuel are delivered by slots in the internal cylindrical case. The hot decomposition products and cooling water steam are removed through the openings in the cylindrical external case. One end of each chamber is connected with a periodically opened, obliquely located jet nozzles generating torque. Disk parts of the casing contain the bearings and pipes delivering cooling water steam and pilot fuel. The engine can work in a wide range of rotational speeds reaching the highest efficiency at resonant conditions. The flow process inside single reaction chamber has following phases schematically shown in Fig. 4. Initially, chamber contains high temperature water steam left after expansion phase. Cooling and separating water steam is delivered from one side extracting hot water steam outside the chamber through its opposite side. In the next phase instead of cooling water steam, the hydrogen peroxide vapor is delivered, pushing out the cooling water steam. After filling the chamber, both longer sides of reaction chambers are closed, ignition is realized starting the decomposition process.

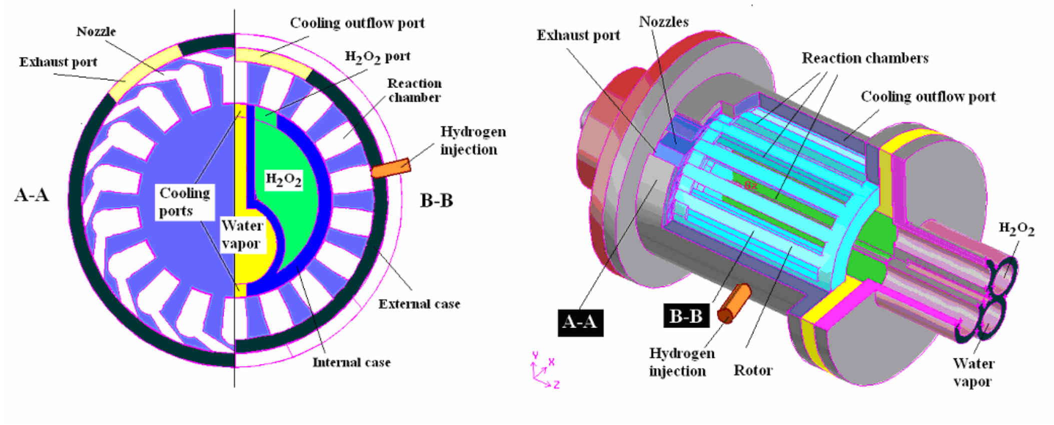

Fig.3: Possible micro engine construction

During that phase pressure inside the chamber is increasing in a wavy way. Temperature is high only in areas containing hydrogen peroxide decomposition products (water vapor and free oxygen). After some delay time the hydrogen is injected into zones in reaction chamber containing free oxygen. Free oxygen reacts with hydrogen in condition (high temperature) guarantee the stable unsteady hydrogen combustion. Two types of reaction fronts exists. The first is the hydrogen peroxide decomposition front and the second is the hydrogen-oxygen reaction front. After full hydrogen peroxide decomposition and hydrogen combustion, high pressure in reaction chamber is build up and the expansion process begins. Expansion through the oblique nozzles located at one of short reaction chamber sides generates torque. After end of expansion phase the cycle is repeated.

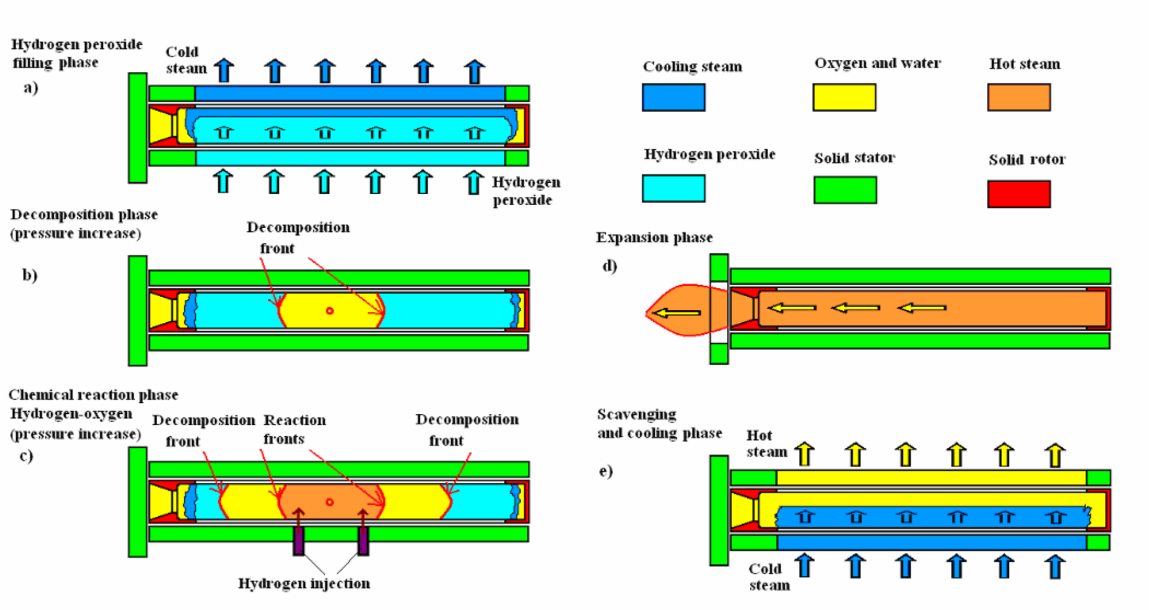

Fig. 4: Five phases of single reaction chamber operation.

The most important, in considered cycle of reaction chamber operation, is realization of cross-flows during the cooling and filling phase, which dramatically reduce the total time of the cycle. Using the stable pilot reaction of hydrogen peroxide decomposition for stabilization of the unsteady chemical reaction of hydrogen-oxygen is a new feature of the micro-engine. Application of a water vapor as a cooling medium warrants clean output of exhaust gases into environment. Only the water vapor is ejected to the atmosphere.

5. Numerical Simulation - Models

All simulations were performed with FLUENT program. The physical model of the compressible fluid takes species transport into account. Three species were considered: hydrogen peroxide, oxygen and water vapour . The flow was treated as unsteady. The simulation of chemical reaction dynamics was based on a turbulence-chemistry interaction model. Thermal diffusion and full multicomponent diffusion was taken into account.

Decomposition of the H_2O_2 was modelled as a single, volumetric reaction process with pre-exponential constant equal 1.0e13 and activation energy 1.8e8 (J/Kg/mol) [6]. As the second process single reaction model of hydrogen-oxygen combustion was applied with the pre-exponential constant equal 9.87e8 and activation energy 3.1e7 (J/Kg/mol) Reaction of finite rate/eddy dissipation type was used with mixing rate coefficient A=4 and B=0.5. The combustion is treated as limited by the mixing process. The chemical reaction rate is governed by the large-eddy mixing time scale, k/ε .

6. Results of 2D and 3D calculations

Simulations of simplified 2D and full 3D versions of a single reaction chamber with sequentially changed boundary conditions were performed simulating all phases of operation. During filling phase strong cross flow in the chamber is generated.

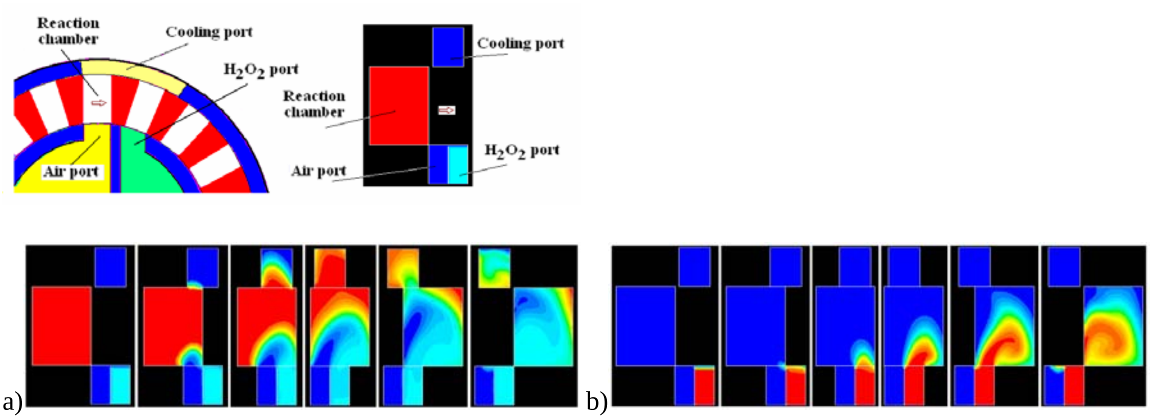

Fig. 5: Gas temperature (a) and hydrogen peroxide concentration (b) in chamber cross-section at cooling and filling phase

The process of cooling and fuel filling was analyzed in a plane perpendicular to the main axis (see Fig. 5). The bottom left channel shown in Fig 5 contains water vapor at temperature 373 K used as a cooling and separating medium and the bottom right channel is filled with hydrogen peroxide at temperature 423 K. The time of H_2O_2 decomposition and hydrogen afterburning is the dominating time in the cycle. Thanks to the cross flow idea, cooling, cleaning, and filling of the reaction chamber with pilot fuel takes only 20% of the working cycle time. The micro engine (10 mm rotor diameter) can generate up to 35 W of mechanical power rotating at 75 000 rpm. The estimated power to volume ratio is about 10 W/cm^3 and the power to mass ratio is about 4 W/g.

7. Conclusions

The presented micro engine idea contains set of breaking innovations 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. Hydrogen peroxide exotermical decomposition is used as a pilot process stabilizing the hydrogen-oxygen chemical reaction. Water vapor is used as a cooling medium which with used fuel components guarantee a clean and environment friendly output of hot gases (only the water vapor) .

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