NUMERICAL INVESTIGATION OF THE RADIAL DISK INTERNAL COMBUSTION ENGINE

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Abstract: This work presents a numerical analysis of the flow and combustion phenomena inside the Radial Disk Internal Combustion Engine. In the set of arch chambers forming the engine disk a mixture of hydrogen peroxide with hydrogen is burned under constant volume conditions. The thermal decomposition of hydrogen peroxide is used as a pilot and stabilizing process of the hydrogen combustion, addressing effectively important challenges for the small dimensions of the channels. The cycle consists of the filling process preceded by the cooling and separating process that is realized by injection of water steam, the combustion, and the expansion process. In the considered numerical model, the cycle is simulated numerically with the commercial software package FLUENT, including the species tracking and reaction. The inner rotating part of the engine, the disk, is modeled as a moving grid geometry that exchanges flow streams with ports located in the stationary part of the engine, the housing. Sealing, ignition, and quenching problems are considered in the model. Results of simulations are presented in form of pressure, temperature, velocity, and species concentration contours as well torque variation in time.

Keywords: Unsteady combustion, Wave disc engine, Shock waves, Modeling

INTRODUCTION

The problem of micro engines is considered for many years. It has been recognized that in low scale, wave machines have some advantages in comparison with its steady flow machine equivalent. To further explore the potential a numerical model of a radial Disk Internal Combustion Engine was build and analyzed. In the proposed technical solution where a set of arch chambers form the engine disk, a mixture of hydrogen peroxide with hydrogen is burned under constant volume conditions. This incorporates two new features compared to the previously introduced Micro Ring Engine [1]. First it is the radial configuration similar to the Radial Wave Rotor and Wave Disk Engine concepts [1, 2, 3, 4, 5] and second it is the utilization of the reaction heat and products of the hydrogen peroxide decomposition to initiate and control a subsequent more powerful oxidization of hydrogen. With this the thermal decomposition of hydrogen peroxide is used as a pilot and stabilizing process of the hydrogen combustion, addressing effectively important challenges for the small dimensions of the channels. The mixture of hydrogen and hydrogen peroxide is inactive until the decomposition process is initiated in combustion chamber by the decomposition products from the preceding chamber. Then oxygen being the result of the decomposition process at the high temperature reacts subsequently with hydrogen. Successful hydrogen peroxide decomposition is a required condition for the realization of the hydrogen combustion.

MOTIVATION

A Comparison of the Joule (or Bryton) cycle with the constant volume combustion (or Humphrey) cycle is shown in Fig. 1.

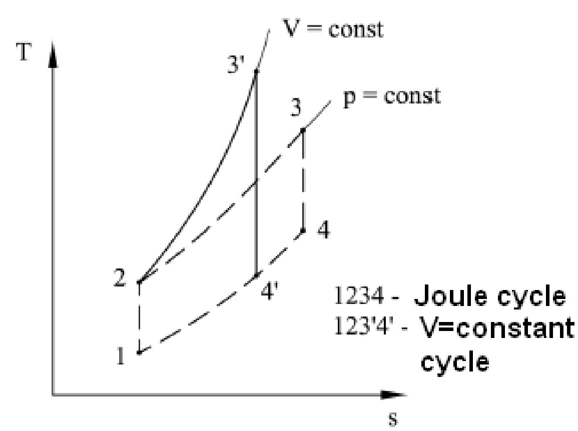

Fig. 1: Comparison of the Joule cycle with the constant volume combustion cycle in a T-s diagram

Comparing the efficiency of the Joule cycle

$$\eta_J = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\pi^{\frac{k-1}{k}}} \quad \text{where} \quad \pi = \frac{p_2}{p_1}$$

with the efficiency of the cycle with combustion at constant volume and same compression ratio π

$$\eta_{v=const}=1-k\frac{1}{\pi^{\frac{k-1}{k}}}\frac{\lambda^{\frac{1}{k}}-1}{\lambda-1} \quad \text{where } \lambda=\frac{T_3^{'}}{T_2}=\frac{p_3^{'}}{p_2}$$

it can be proven the latter cycle is more efficient because of the resulting relation

$$k\frac{\lambda^{\frac{1}{k}}-1}{\lambda-1}<1$$

This motivated the numerical modeling of the internal combustion wave engine.

PROPOSED ENGINE CONSTRUCTION

Taking into account many previous investigations [1, 2, 3, 4, 5] it was decided that following engine geometry and flow sequence had to be realized. The cycle (Fig. 2) consists of (1) the filling process preceded by (2) the cooling and separating process that is realized by injection of water steam, (3) the combustion, and (4) the expansion process. It is simulated numerically with the commercial software package FLUENT, including the species tracking and reaction. The inner rotating part of the engine, the disk, is modeled as a moving grid geometry that exchanges flow streams with ports located in the stationary part of the engine, the housing. Sealing, ignition, and quenching problems are considered in the model.

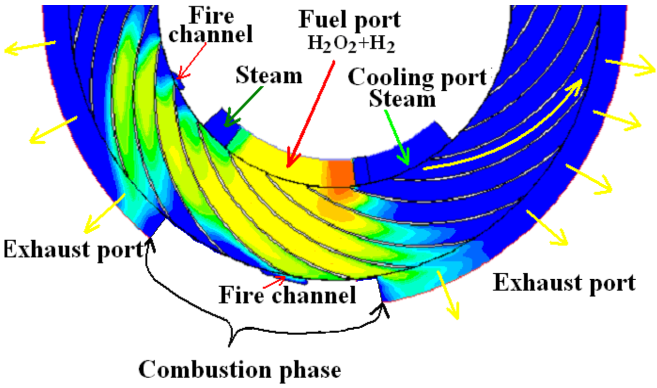

Fig. 2: Cycle Schematic of lower half of a two cycle per revolution Radial Disk Internal Combustion Engine.

Starting from the phase at which the disk cell is filled with the high temperature expanded gas from previous cycle of operation, the injected steam stream is used to cool the cell and form a separating area between exhaust gases and the fuel.

Then the fuel being the mixture of the hydrogen peroxide and hydrogen is injected into the cell. Finally depending on the analyzed case additional a small stream of steam enters to prevent the early ignition by the high temperature exhaust gases moving in the gap between the disk and case.

PRELIMINARY TEST

First, a simplified model having only two cells was considered (see Fig. 3). Simulations of the expansion process from a pressure of 0.6 MPa and temperature of 1000K were performed for different rotational speeds of the disk.

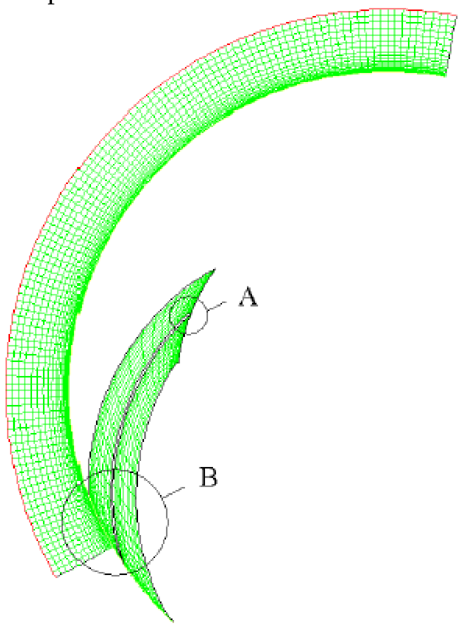

Fig. 3: Mesh of simplified model for preliminary tests.

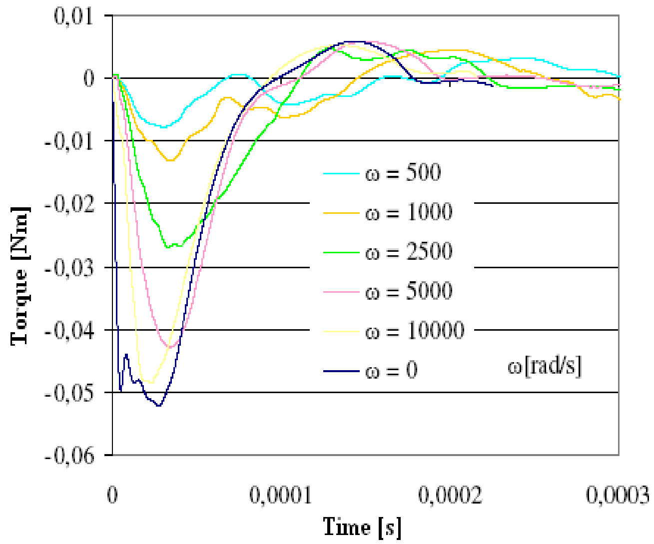

Fig. 4: Relation between the disk speed and torque developed during the expansion process

Results of the simulation are presented in Fig. 4. The results can be interpreted in following way. The maximum torque for the zero rotational speed has been obtained at assumption of immediate opening of the outer cell side. For all other results presented in Fig. 4, the opening time was function of the rotational speed. As it can be clearly seen, the torque generation is a function of the opening time. Shorter opening time results in higher torque developed.

FULL MODEL

The heat loss through the cell walls significantly influences the operation of the engine. Since the simulations were performed only in a two dimensional model, that can only directly account for the heat transfer through the inner and outer case walls, additional negative heat source were applied by the UDF routine representing the heat losses through the side walls (top and bottom) of the cells. The heat conduction coefficient was estimated from simulation results on another other engine surfaces.

Ignition of fuel, except the initial step, have been realized through the fire channels located in the engine case through which due to the pressure differences the high temperature gases enter the cell filled with fuel mixture and cause the ignition. The position of the fire channel is shown in Fig. 5.

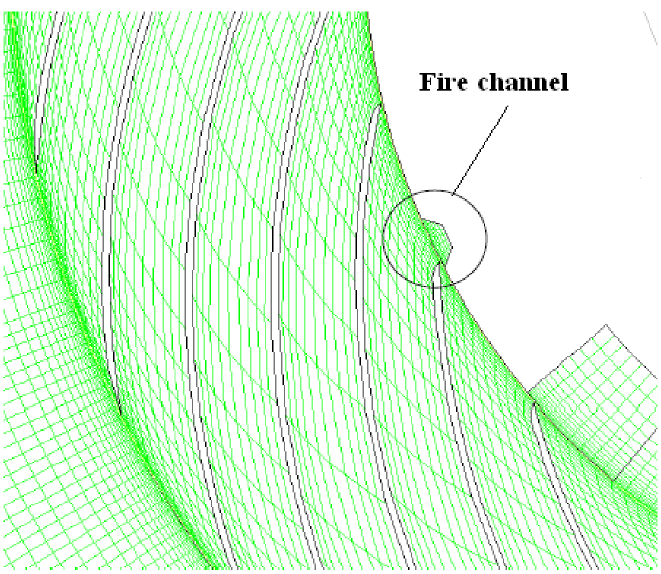

Fig. 5: Fire channel position

RESULTS OF NUMERICAL CALCULATIONS

Some results of numerical simulation are presented in Fig. 6 (contours of temperature), Fig. 7 (contours of pressure distribution) and in Fig. 8 (species distribution).

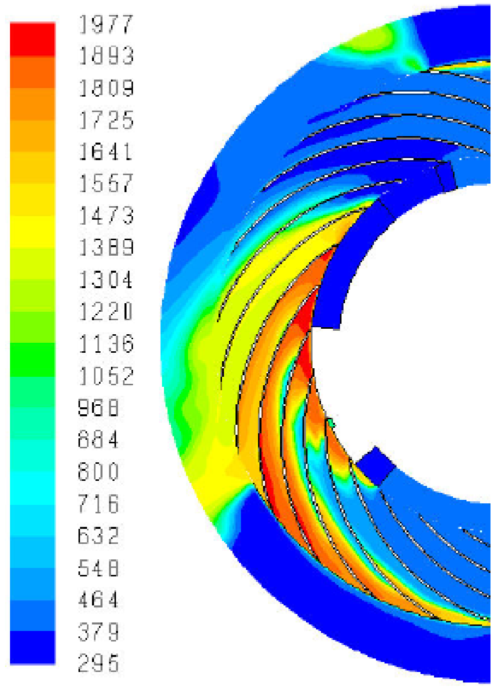

Fig. 6: Contours of the Static Temperatures

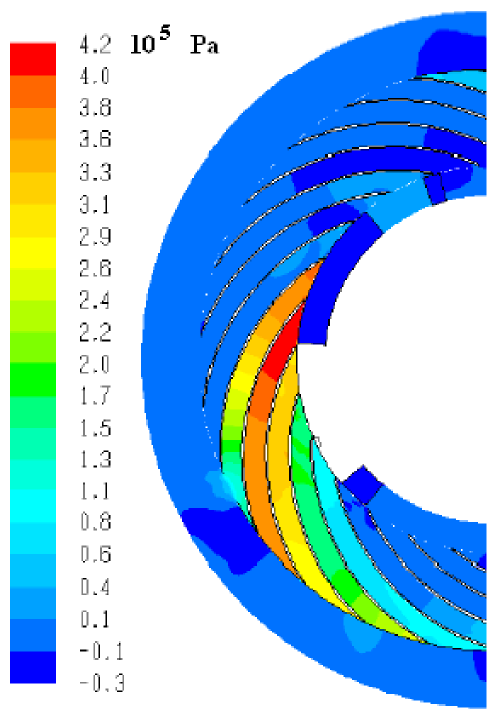

Fig. 7: Contours of the Static Pressures

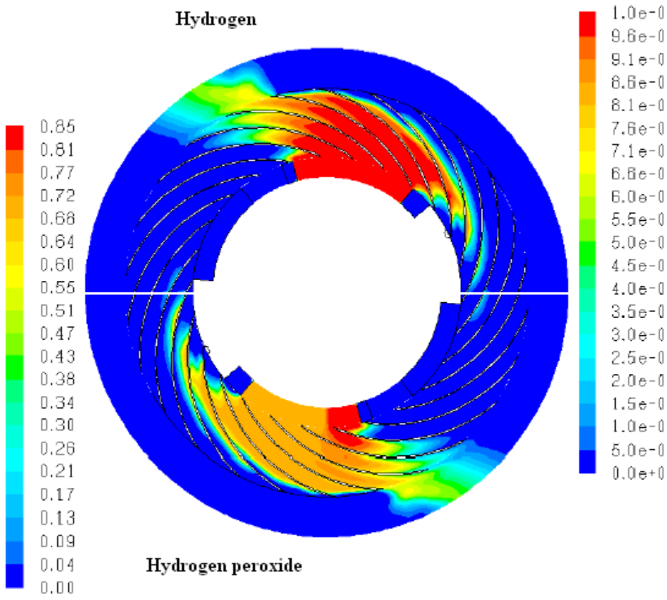

Fig. 8: Contours of Hydrogen and Hydrogen Peroxide Fractions

Investigation in the influence of the duration of the combustion phase (see Fig. 2) on the torque generated by engine were performed and results of are shown in Fig. 9. It can be noticed that there exists an optimal duration of this phase.

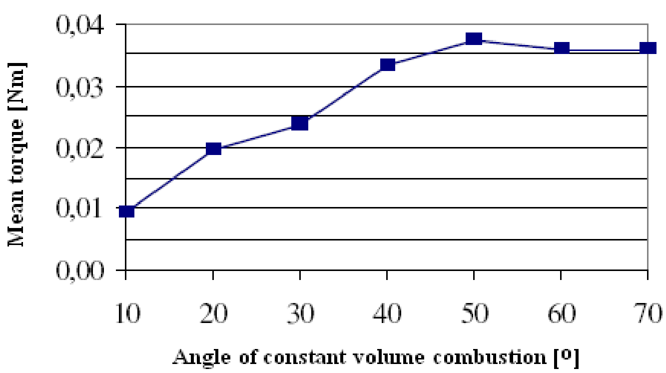

Fig. 9: Relation between the Torque Generated and the Angle of Constant Volume Combustion

DISCUSSION

The paper presents numerical investigations in support of the development of a micro-engine that is based on an internal combustion radial disk configurations. The simulations revealed a range of challenges like: heat losses, leaks, flame propagation turbulence dependence, rotational speed dependence, duration of combustion processes. The simulation of the combustion process inside the engine cell is a challenging and need to be correlated with appropriate experiments. Generally it was shown that an engine of such configuration can realize a stable combustion and torque generation. A great loss of fuel was observed during the filling phase. The engine geometry needs to be further optimized.

CONCLUSION

Considering the achieved results it appears promising that revealed challenges can be solved through continued investigations.

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