CERAMIC WAVE MICRO ENGINE – FEASIBILITY STUDY

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Abstract: The wave disk engine's construction was analyzed assuming ceramic material was used for its construction. The efficiency of a micro-engine strongly depends on the pressure ratio. High temperatures in the combustion chamber are required in order to compensate for unavoidable leaks between the rotor and stator. Temperatures that are reachable only by using ceramic materials were considered. The engine construction was modified and adapted to the specific requirements of the ceramic material. The combustion chamber, gas passages and ports function in steady state conditions. The wave rotor chambers spin at 20,000 rpm and operate in unsteady and oscillating gas flows having temperatures varying between 300 K and 3000 K. Such thermal and load conditions are challenging for ceramic materials.

Gas dynamic processes are analyzed in the engine geometry designed for use with ceramic materials and technology. A feasibility study was performed in which different ceramic materials were used for the stator and rotor, taking specific requirements into account.

Keywords: unsteady compression, wave disk

INTRODUCTION

The thermodynamic Brayton cycle describes the processes realized in turbo-engines. The thermodynamic efficiency of this cycle depends on the compression ratio. On a small scale, turbo-engines have a simple construction and due to that operate at low compression ratio which is the main reason for their low overall efficiency.

The maximum temperature reached in the turbine is limited by the properties of material used on turbine blades. Typically rotational speeds of turbines are very high, generating high blade loads due to centrifugal forces.

The wave engine can be a rational equivalent of a turbo-engine but employed on a micro scale [4, 5].

In our proposed wave engine configuration, a single stage compression device reaches a compression ratio of 4-5, which is rather impossible for a single radial compressor on a low scale device. The wave rotor disk is self cooled, which means that the passing gas temperature can be higher than the mean disk wall temperature. The rotational speed of wave disk is three times lower than comparable turbo-compressor unit, which means nine times lower load due to centrifugal forces. In such circumstances the use of ceramic materials for disk and case seems reasonable.

It is proposed to design a ceramic wave engine with the high temperature heat source realizable by sun beams concentrated by a set of mirrors.

PROPERTIES OF CERAMIC MATERIALS

The primary motivation of using ceramic materials for the wave disk engine is their refractoriness, or resistance to high temperatures. However, they are generally not strong in tension and we must consider their mechanical properties in detail. Table 1 shows Young's modulus of elasticity and Poisson's ratio for some ceramic materials.

Table 1: Young's modulus of elasticity and Poisson's ratio for some common ceramics [6]

Ceramic	Young's modulus(GPa)	Poisson's ratio
ZrO_2	200	0.31
SiO_2	73	0.17
BeO	353	0.2
MgO	280	0.27
ThO_2	240	--
Al_2O_3	366	0.18
Mullite	220	0.27
Spinel	250	--

Ceramics are widely used for linings of furnaces and any other place where the onus is on low heat conductivity and infusibility at high temperatures. These ceramics are often referred to as refractory ceramics. The typical physical and thermal properties of some such ceramics are tabulated in Table 2.

CERAMIC MATERIAL PROCESSING

The fabrication of any ceramic product involves the following steps:

1. Preparation of a ceramic powder and liquids or organic additives: Ceramics used in technical processes are prepared from ceramic powders such as zirconia or alumina. We have considered zirconium tungstate as a possible powder for use in our process. Some additives are often added to improve plasticity during shaping or machining.

2. Adaptation of the system to the shaping process: This involves grinding, mixing, dispersion, and granulation of the powder base. The granule size of the powder is of particular concern here.

Table 2: Thermal and physical properties of some ceramics [6]

Product type	Clay	HTA Group 1(Corundum, Mullite etc.)	Alumina/carbon based
Bulk density(g/cm^3)	2.25	2.75	3.09
Open porosity (%)	16.5	20	10.5
Compressive strength (MPa)	65	90	59
Refractoriness under load (° C) (under 0.2 MPa)	1450	1460	-
Permanent linear change at 1450 °C/5h (%)	+0.1	+0.3	0
Thermal expansion at 1000 °C (%)	0.65	0.71	0.7
Thermal conductivity at 1000 °C (W/mK)	1.4	2.2	4
Specific heat between 20-1000 °C (kJ/kg K)	1.06	1.10	1.11

3. Shaping: The mixed and treated powder is shaped into a final form allowing for change in shape during compaction and sintering. The shaping of the parts for the proposed wave disk engine would involve preparing a mold and the compaction of the ceramic powder into it using a uniaxial dye.

4. Drying to eliminate organic additives: Some of the additives are only added to improve plasticity and generally facilitate shaping in a mold. These are removed before sintering by drying.

5. Sintering: Ceramics gain their high compressive strength and hardness after they have been subjected to a high temperature (typically over 1500 °C) over a period of time. This process is called sintering. The design of the wave disk engine is too complex to be obtained just by the preparation of a suitable mold. There are several ceramic powders which can be machined in a partially sintered state. The strategy for fabrication of our wave disk would therefore be preparing a cast of suitable dimensions, partially sintering it to render it machining, machining it to a final form and then sintering it to obtain the most suitable mechanical properties.

NUMERICAL SIMULATIONS

The geometry of a wave engine was presented in detail previous publications [1, 2, 3] so we only basic information about results of numerical simulations are presented. A numerical model of unsteady flows in rotor and stator part of the proposed wave engine was prepared and simulation with the help of the commercial CFD code FLUENT. A full geometrical model of the flow field was prepared in Gambit. Transfer of flow data between the rotating and steady parts of the flow field was realized using the interface technique. Heat release was simulated by the radiator model described by the heat source temperature and heat transfer coefficient. On inlets the pressure inlet boundary conditions were applied and at outlet the pressure outlet conditions. Spalart-Allmaras turbulence model was used for simulation of turbulent flow inside engine with the level of turbulence on the inlet equal 5% and turbulence scale 1 mm.

In Fig. 1 and in Fig. 2 instantaneous pressure and temperature distributions are presented. One can notice a pressure inside the heating passage on the level of over 3 bars, instantaneously reaching 4.5 bars and maximum gas temperature of 2000 K.

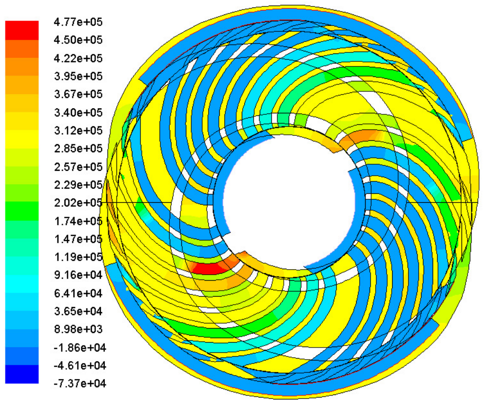

Fig. 1: Instantaneous pressure distribution in engine channels and passages in Pascals

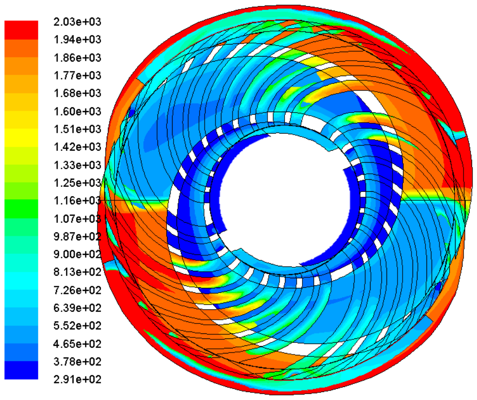

Fig. 2: Instantaneous temperature distribution in engine channels and passages in Pascals

In Fig. 3 variation of the static pressure inside the heating chamber is presented showing a compression ratio over 4.0 which corresponds to the Brayton cycle efficiency about 0.33.

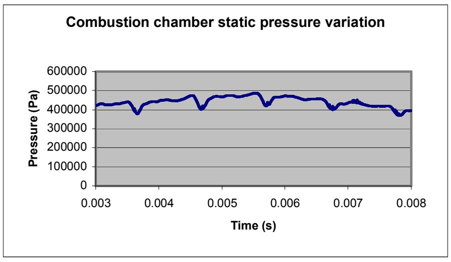

Fig. 3: Variation of static pressure inside the combustion chamber

A wave disk engine with disk diameter 120 mm and thickness 10 mm rotating at only 20,000 rpm can generate power up to 950 watts with efficiency of about 10%.

CONCLUSIONS

The wave disk engine will be subjected to extremely high temperatures and mechanical stresses. The utilization of ceramics for this purpose is therefore of some benefit but also throws up some challenges. Therefore, the design of the engine must include not just an investigation of flow and combustion but also a strength and failure analysis of the external structure. This will be an important component of our study in the future.

REFERENCES

[1] Piechna J, Dyntar D 2007 Two-dimensional Numerical Analysis of the Wave Jet Micro-Engine Operation, *Proc. PowerMEMS 2007 (Freiburg, Germany, 2007)*

[2] Piechna J, Dyntar D 2008 Numerical Investigation of the Wave Disk Micro-Engine Concept *International Journal of Gas Turbine, Propulsion and Power Systems, December 2008, Volume 2, Number 1*

[3] Piechna J 2008 Micro Ring-Engine Numerical Fluid Dynamics Analysis, *Proc. PowerMEMS 2008*

[4] Piechna J, Akbari P, Iancu F, Müller N 2004 Radial-flow wave rotor concepts, unconventional designs and applications *Proc. IMECE 2004, IMECE2004-59022* Anaheim, California

[5] Iancu F, Piechna J, Dempsey E, Müller N, Ultra-Micro Wave Rotor Investigations, *Proc. PowerMEMS 2005, pp. 93-96* Nov. 28-30, 2005 Tokyo, Japan

[6] Boch P, Niepce J N 2007 *Ceramic Materials: Processes, Properties and Applications* (John Wiley and Sons)