

MBDA R&T EFFORT ON PULSED AND CONTINUOUS DETONATION WAVE ENGINES

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Abstract: The continuous detonation wave engine (CDWE) can be considered to reduce the environmental conditions generated by pulsed detonation engine (PDE) while reducing the importance of initiation issue and simplifying some integration aspects. Specific experimental programs are performed by MBDA and Lavrentiev Institute to study CDWE operating mode and to address some key points for the feasibility of an operational rotating wave engine for space launcher. It is found that such engine can deliver impressive thrust in a very small package (275 daN for internal diameter of 50 mm and length of 100 mm, kerosene-oxygen engine) and that can be increased with the use of a diverging nozzle. Due to the geometry of the combustion chamber, a plug or aerospike nozzle seems to be the best design, the thrust vectoring capability of this engine (with the local change of the mass flow rate) being a way to solve the problem of attitude control. The heat fluxes are very high but located mostly near the injection wall. This point will help the gasification of the liquid component injected inside the combustion chamber. Some preliminary tests are performed to evaluate the capability of C/SiC composite materials to sustain the very severe mechanical environment generated by the rotating detonation waves. Beyond these first steps, a large scale ground demonstrator allowing to address all issues for a continuous detonation rocket engine using LH₂/LO_x mixture is designed by MBDA. As the first step toward the development of this large scale engine, a small scale demo is tested in Spring 2010.

Key words: detonation wave engine; propulsion; performance model

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INTRODUCTION

During past years, MBDA performed some theoretical and experimental works, mainly in cooperation with Laboratory of Combustion and Detonation at National Superior School of Mechanics & Aerospace in Poitiers, on pulsed detonation engine (PDE). These studies aimed at obtaining a preliminary demonstration of the feasibility of PDE in both rocket and airbreathing modes and at verifying the interest of such PDE for operational application; rocket and airbreathing mode experimental evaluation, effect of filling coefficient, effect of a nozzle, thermal, mechanical, acoustic and vibrations environment generated, evaluation of different fuels, performance code development.

Due to its thermodynamic cycle, PDE has theoretically better performance than another

classical propulsion concept using the combustion process (20% to 25% in term of thermal efficiency). Nevertheless, it is necessary to verify that this advantage is not fully compensated by the difficulties, which could be encountered for practical use of PDE concept or by the complex technology, which could be needed to implement in an operational flying system.

Indeed, PDE performance is driven by the following parameters:

- (1) Quality of the pre-mixing;
- (2) Value and nature of the needed energy for igniting the detonation;
- (3) Duration of the high pressure level (depending of the filling coefficient);
- (4) Maximum operating frequency depending of the minimum filling time.

And it is not so evident to optimise each of

these parameters to obtain a real improvement of the global efficiency.

Moreover, PDE generates a severe vibration environment, which can imply higher more severe requirement for all on-board vehicle equipments or subsystems.

After some in house studies performed in national and international cooperation^[1], MBDA is now cooperating with Defense Singaporean Organization (DSO) to develop a demonstration engine in order to really assess the feasibility and the interest of this propulsion concept.

Many authors are focusing their work on high performance concepts in order to take advantage of the high theoretical performance of PDE. That generally leads to complex arrangements and needs to optimize each of the main parameters of the engine. Such a propulsion systems correspond with high development and production and maintenance costs.

Considering that :

(1) Well known existing propulsion systems (rockets, turbojets, ramjets) have high performance and are still being improved.

(2) For each application, related vehicles have been optimized to take the better advantage of these existing engine concepts.

MBDA and DSO do not aim at obtaining the maximum engine performance but try to take advantage of the specific characteristics of PDE to simplify engine and vehicle conception.

The considered application is an engine able to power a reusable subsonic UAV with cruising and loitering mission which corresponds with very demanding requirement in term of thrust range^[2-3].

The use of rotating detonation wave can also be considered to reduce the environmental conditions generated by PDE while reducing the importance of initiation issue and simplifying some integration aspects.

Compared with PDE, this design allows an easier operation in reduced-pressure environment and an increase in engine mass flow rate and thrust-to-weight ratio.

Such a concept has been studied for a long time, particularly at Lavrentiev Institute for Hydrodynamics (LIH) in Novosibirsk. As it was done for PDE, specific experimental program has been performed by MBDA and Lavrentiev Institute to understand unsteady, 3-D flow behind the detonation wave and to address some key points for the feasibility of an operational rotating wave engine for space launcher :

(1) Two-phase mixture detonation ;

(2) Operating limits (injection pressure for example) ;

(3) Noise generated by the continuous detonation wave engine (CDWE) operating at several kHz ;

(4) Heat fluxes (intensity, areas) and cooling strategies ;

(5) Composite materials (Carbon/Silicon Carbide) compatibility ;

(6) Engine thrust vectoring capability.

On the basis of these results, a preliminary design of an operational engine is performed by taking into account all engine/airframe integration issues in order to optimize the benefit of detonation wave engine.

In order to better assess the feasibility of such a system, specific experiments are performed to address some key points like thrust vectoring, heat fluxes and material compatibility, operation in low pressure environment^[4-6]. In parallel, a dedicated effort is undertaken to develop an adapted numerical simulation tool.

Beyond these first steps, and with the partial support of French Space Agency CNES, MBDA designed a large scale ground demonstrator allowing to address all already mentioned issues for a continuous detonation rocket engine using LH₂/LO_x mixture.

1 CDWE OVERVIEW AND GENERALITIES

The main feature of CDWE is an annular combustion chamber closed on one side (and where the fuel injection takes place) and opened

at the other end. Inside this chamber, one or more detonation waves propagate normally to the direction of injection (Fig. 1).

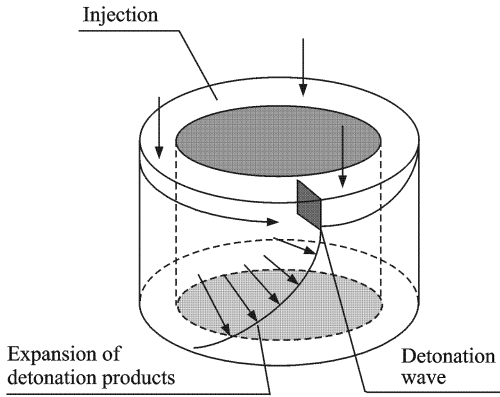


Fig. 1 CDWE principle

In fact CDWE is very close to a multitube PDE cluster running globally at very high frequency (typically several kHz) and so the mean pressure inside the chamber is higher for a typical single tube PDE (as is the mean thrust per unit area). If for PDE the injection pressure could be as low as the ambient pressure, in the case of CDWE the injection pressure should be higher and this kind of engine is particularly well suited for rocket operation.

The flow inside this chamber is very heterogeneous, with a 2-D expansion fan behind the leading shock (Fig. 2). The transverse detonation wave (BC and $B'C'$) propagates in a small layer of fresh mixture (AB') near the injection wall. An expansion fan is then created and transforms the tangential speed of the hot gas in axial speed 5 (Fig. 3). The necessary condition for the propagation of a detonation wave is the continuous renewal of the layer of combustible mixture ahead

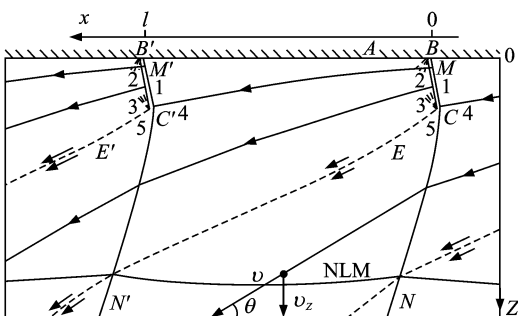


Fig. 2 Flow field in TD wave reference axis

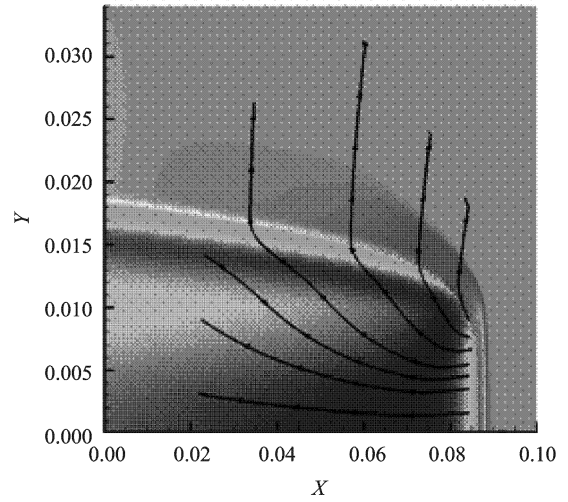


Fig. 3 Flow field in laboratory reference axis

TDW. The height of this layer h must be not less than the critical value h^* for detonation. In the case of a LH_2/LO_2 engine, the dispersion of liquid oxygen droplets and the quick mixing of the components should be fast enough to decrease the value of h^* and to enable the realization of CD in small chambers.

2 SYSTEM STUDY AND ENGINE SIZING

On the basis of a semi-empirical performance model developed by LIH, the comparison between an advanced liquid rocket engine (LRE) and CDWE is done previously by taking the same maximum pressure inside the combustion chamber of both engine (and not the same injection pressure).

It is found that the needed combustion chamber length for stabilizing the detonation process, could be very short, shorter than 200 mm and even close to 100 mm with H_2-O_2 mixture. Such a short combustion chamber length will be helpful to reduce the wetted area of the engine because a annular chamber exhibits an inherently greater wetted area than a classical combustion chamber of the same length.

With the capability to use a reduced length combustion chamber (and a smaller wetted area), CDWE will have a slightly increased design flexibility than a conventional LRE, with the possibil-

ity to minimize the engine heat losses.

From a performance point of view, for a given maximum pressure inside the combustion chamber, the detonation cycle gives 15%–20% higher temperature and a lower burned gas molecular mass so the exhaust velocity is higher than with LRE. But reduced feeding pressure can also be used (here 2.2 MPa instead 7.0 MPa) with still interesting performances as shown in Table 1.

The difference between CDWE and LRE vacuum performance decreases as nozzle exit size increases (expansion rate being more limited for a

Table 1 Comparison of achievable performance

d_n/m	S_n/S_1	p_n/p	v_n/v_z	I/s	I^*/s	J/kN	J^*/kN	$\Delta J/J^*$
0.4	1.333	0.633 7	1.10	326	296	107.97	98.01	0.101
1.1	10.08	0.039 9	1.486	396	383	131.10	126.73	0.034
2.15	38.5	0.007 3	1.623	424	415	140.06	137.05	0.022

* related to reference LRE – ER = 1

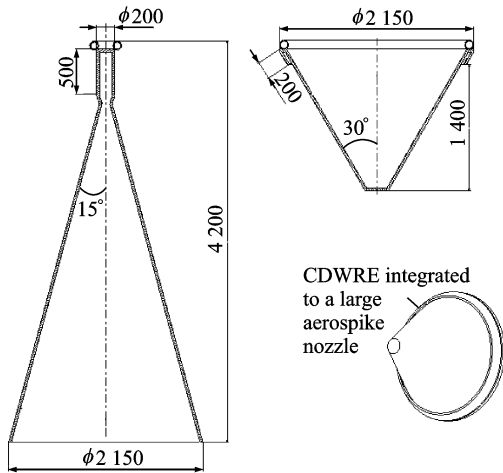


Fig. 4 Comparison between CDWE and equivalent classical LRE

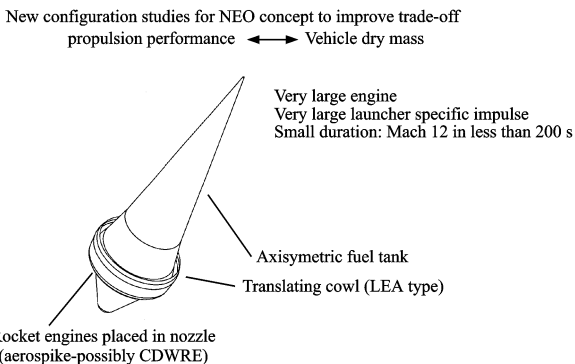


Fig. 5 Fully axisymmetric airbreathing space launcher NEO

same detonable mixture mass flow).

Moreover, the integration of continuous detonation wave rocket engine (CDWRE) can be very attractive when considering an aerospike configuration as shown in Fig. 4. Such system would be particularly well adapted to power the fully axisymmetric airbreathing space launcher proposed by MBDA^[7], as shown in Fig. 5.

In order to better assess the real interest of CDWE for space launcher application, some specific action is led to develop a global performance design tool. In the first step, the simplified performance model developed by LIH is adapted to

determine achievable performances. ICARE Lab is developing a more accurate model and first results are provided by Ref. [8]. Application of this model to the case of H_2/O_2 mixture allows to assess achievable performances (Fig. 6). By another way, ICARE Lab performed a dedicated study to optimize the annular nozzle^[9].

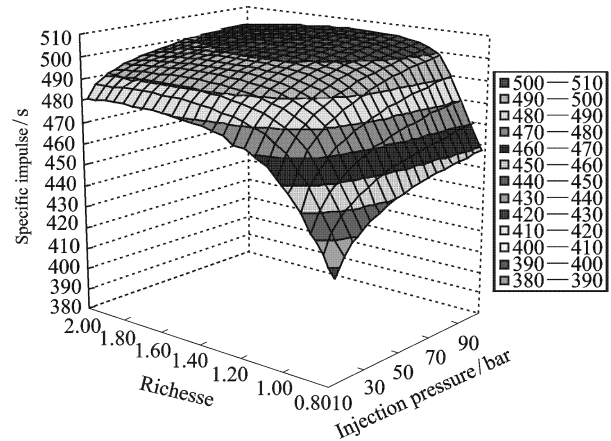


Fig. 6 Achievable performance for H_2/O_2 continuous detonation wave rocket engine

3 EXPERIMENTAL WORKS

Using the mock-up design principle described by Fig. 7 and the test bench shown in Fig. 8,

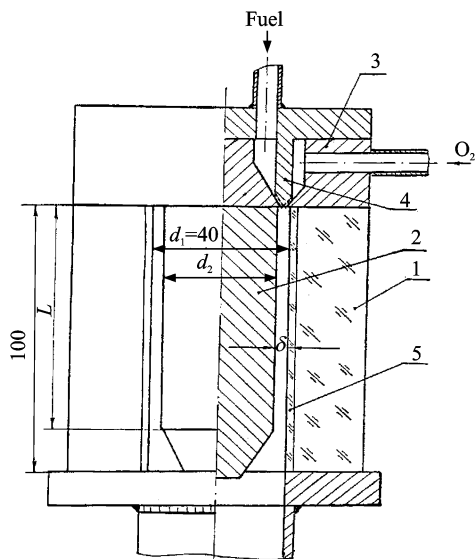


Fig. 7 Mock-up design principle

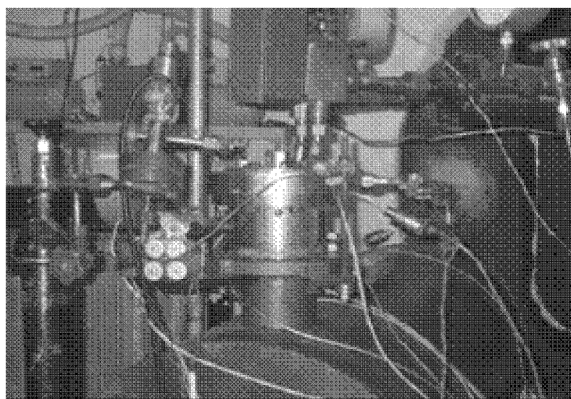


Fig. 8 General view of test bench at LIH

some basic experiments are first performed with LIH, taking advantage of their long experience in such a experiment:

(1) Experiments in combustion chamber (CC) with inner diameter of 50 mm, 100 mm and 280 mm.

(2) Homogeneous (gas/gas) and heterogeneous (liquid/gas) mixture studied.

The experimental detonation chamber is fed with fuel and oxidizer supplied by pressurised tanks blow-down. Due to this, the test duration is limited (< 1 s) and the test conditions are rapidly changing (Fig. 9). In fact, as the process is very rapid, this operating mode is not an issue for the test validity (except maybe the total duration which can limit the heating of the wall preventing, maybe, possible isobare combustion). On the contrary, it provides a large variation of

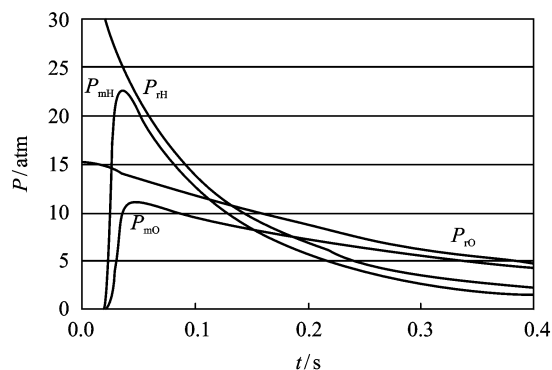


Fig. 9 Typical feeding conditions evolution during test run

pressures and equivalence ratio, which allow proving the stability of the detonation process over a large range of feeding conditions.

Some main obtained results are:

(1) Detonation regime obtained in 100 mm diameter CC with GH_2/LO_x ;

(2) Detonation regime obtained in 330 mm diameter CC with kerosene/air;

(3) High thrust density achieved in small CC (275 daN for a 50 mm inner diameter kerosene/ GO_2 engine).

From these experiments, some key points can also be derived for the general sizing of a CD-WE combustion chamber:

(1) The height of the fresh mixture layer h is a function of the detonation cell size.

(2) The frequency of the engine is given by the ratio D/l , where D is the detonation velocity and l the distance between two consecutive detonation waves, typically several kHz, the length of the combustion chamber L should be longer than 80% of l (to ensure transition from subsonic to supersonic inside the CC). If not the detonation could be unstable.

Thanks to the blow-down operation, it is also easy to get a detailed knowledge of the stability domain of the detonation process. As an example, Fig. 10 shows the stability domain obtain for a mixture of gaseous Hydrogen and Oxygen as function of specific mixture mass flow (related to the top injection wall area) and of equivalence ratio.

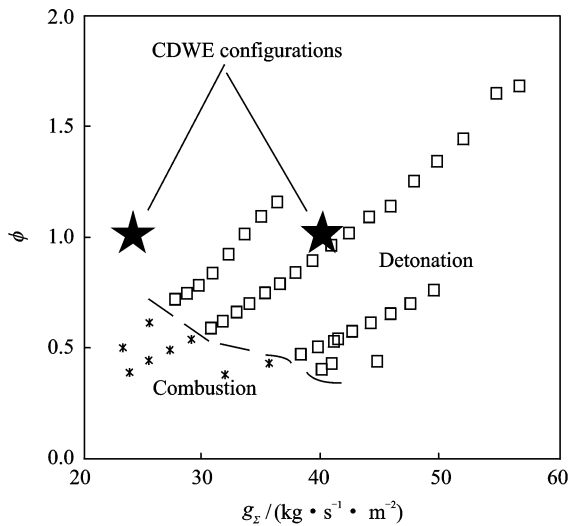


Fig. 10 Stability domain-gaseous H_2/O_2 mixture

In this particular case, it has to be underlined that the detonation waves speed is 2 770 m/s at equivalence ratio 1 when Chapman-Jouguet speed D_{cj} is 2 840 m/s. But equivalent results can be obtained (depending of the injection configuration) with other mixtures as shown in Table 2.

Table 2 Example of detonation wave speed compared with corresponding D_{cj}

Fuel	Propane/ O ₂ (gas)	H ₂ (gas)/ O ₂ (liquid)	Kerosene/ O ₂ (gas)	Kerosene/ O ₂ (liquid)
ϕ	1.00	1.70	0.92	1.22 0.95
$D/(\text{m} \cdot \text{s}^{-1})$	2 270	3 076	2 000	2 460 2 200
$D_{cj}/(\text{m} \cdot \text{s}^{-1})$	2 430	3 170	236	2 520 2 400
Delta/%	6,6	3,3	15,2	2,3 8,3
$G/(\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-2})$	140	—	106	707 1 450

4 SPECIFIC ISSUES

4.1 Thrust vectoring capability

One of the peculiarities of CDWE is that the number of detonation waves inside the chamber is not constant and is a function of the combustible mixture, the combustion chamber geometry and also the mass flow rate. For a given mixture in a given chamber, changing the mass flow rate (and the injection pressure) will change the number of detonation waves inside the chamber.

This could be explained with the assumption that behind TDW (and between two consecutive

TWD), there is a complex series of shock waves. If the mass flow rate is increased, the height of the fresh mixture behind two consecutive detonations is sufficient to support a new detonation wave ($h > h^*$) and a shock induced combustion (a detonation) could occur and a new TDW appears. If the mass flow rate inside the combustion chamber is decreased, the height of the fresh mixture between two consecutive TDWs decreases and could be insufficient to support a shock-induced combustion and TWD degenerates into a more simple shock wave.

This self-adaptation of the detonation to the fresh mixture local mass flow makes it possible to gain thrust vectoring with the local increase of the mass flow. Some experiments are done in a 100 mm internal diameter combustion chamber. The injection wall consists of 190 holes for the injection of fuel and oxidizer. In one series of experiments the equivalence ratio is changed in one half of the engine compared with the other half. In another series, the injectors diameter is increased in order to double the local mass flow rate in one half of the engine.

Eight pressure probes (P_1 to P_8) are located along the circumference of the outer wall of the annular chamber.

In all experiments it is possible to obtain an increase of the thrust on one side of the engine. The most promising experiments show that a 30% increase of the thrust-wall overpressure is possible if the mass flow rate is doubled. This increase is lower than expected but the small diameter of the test engine limits the heterogeneity of the flow inside the combustion chamber. With a larger engine, a 100% increase of the thrust on one side (compared with the other side) should be possible (Fig. 11). A small shift of the maximum and minimum pressure values is also observed. Those extreme value seems to be located between P_7 and P_8 (maximum) and between P_3 and P_4 (minimum) instead of directly near P_1 and P_5 .

Compared with LRE (with a gimbaled

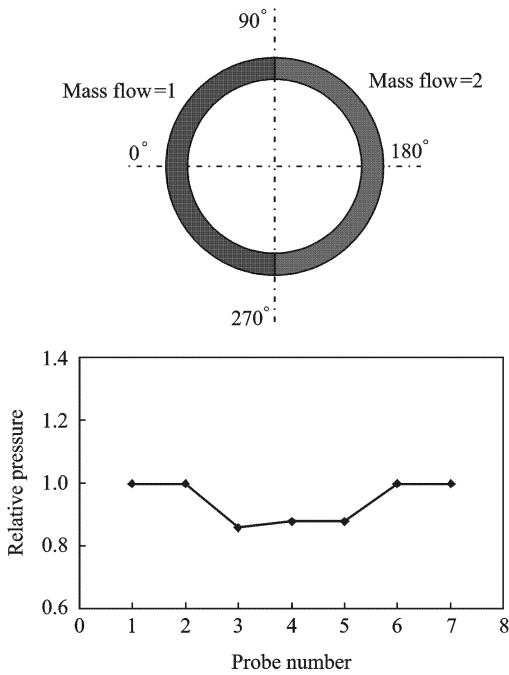


Fig. 11 Pressure evolution along chamber circumference

nozzle), this thrust vectoring capability is interesting because there is no change in the thrust direction and the response time is limited only by the response time of the injectors, which could be very fast, enabling the positive control of the vehicle attitude at high frequency without using much power. The complete pressure field and flow velocity should still be investigated to check the effect of the flow deflection and flow expansion in the nozzle.

4.2 Heat fluxes and cooling system

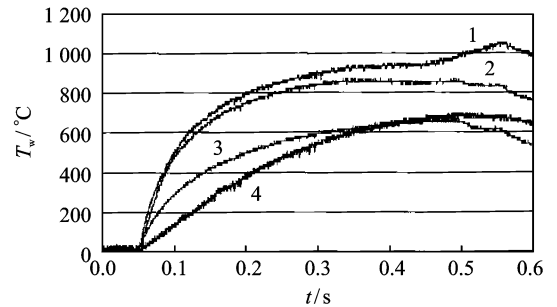
Due to the thin layer of detonation, the highest heat load inside CC occurs near the thrust wall and decreases rapidly along the axial axis.

Wall temperatures in heat-sink combustion chambers are recorded with Hydrogen/Oxygen and kerosene/Oxygen mixtures (Fig. 12). In Fig. 12, point 1 is the detonation wave and points 2, 3, 4 are distributed along an axial line up to exit section.

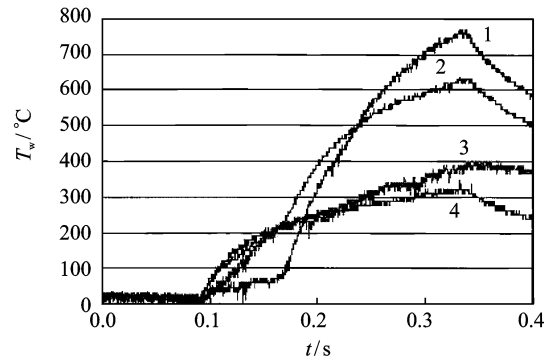
The cooling system design could be critical because for metallic structures the mean heat fluxes near the thrust wall are measured between 12 and $17 \text{ MW} \cdot \text{m}^{-2}$ with local values even higher

(with Hydrogen/Oxygen mixture).

This heat flux repartition is also very different from the one obtained in LRE where the maximum heat fluxes occurs near the combustion chamber geometric throat. This point could be beneficial for the engine design because the vaporization of the injected oxygen will be faster and the mixing between hydrogen and oxygen will be better.



(a) Hydrogen/Oxygen mixture



(b) Kerosene/Oxygen mixture

Fig. 12 Evolution of temperature along axial line during test run

The high heat fluxes anticipated in a CDWE lead to the issue of active cooling, a very difficult task with metallic structures with a wall temperature limited to the vicinity of $1\,000 \text{ K}$. Composite materials could achieve higher wall temperature (up to $1\,800 \text{ K}$) even in oxidizing conditions. After a careful review of existing products, some C/SiC composite materials are selected. Then, two composite parts, constituting the inner wall of the annular detonation chamber, have been designed and manufactured to be tested in the LIH 100 mm CDWE combustion chamber. Each of these two parts successfully sustained a dozen of short duration (0.5 s) experiments with-

out apparent damage to the material surface (Figs. 13, 14). A new experiment series is performed with more severe conditions (feeding pressure up to 2.5 MPa) during which the two samples are damaged proving that this point is surely one key technology issue to be carefully addressed in the future.

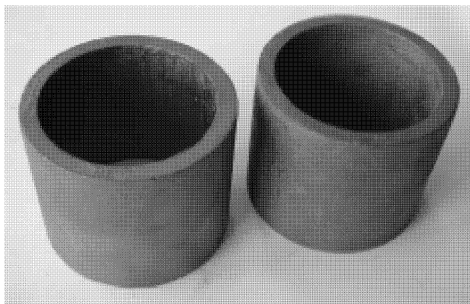


Fig. 13 Two composite parts



Fig. 14 Part installed on chamber central body

4.3 Operation in space environment

Ignition of an engine in very low pressure environment could be a real problem, even for a conventional rocket engine. For CDWE operation, the lack of geometric throat adds to the potential difficulty of a sufficient filling of the chamber with no counter pressure.

This issue is investigated using LIH 100 mm ID detonation chamber connected to a 0.5 m³ vacuum tank with an initial pressure of 6 kPa.

The first step is to investigate the effect of the injection conditions (specific mass flow and equivalence ratio), and after that to decrease the ignition energy until it is impossible to achieve an initiation of the detonation.

Blasting copper wires are used for initiating the detonation inside the combustion chamber and ignition energy could be changed with the change of the applied voltage and the wire diameter.

Gaseous hydrogen and oxygen at ambient pressure are selected for those experiments and injection pressure between 0.16 and 2.50 MPa (for hydrogen), and 0.5 and 1.1 MPa (for oxygen) allowed the investigation of ignition within a wide range of low specific mass flow (between 21 and 57 kg · s⁻¹ · m⁻²). This mass flow rate is ten times lower than mass flow used in previous experiments but is mandatory given the relatively small volume of the vacuum tank.

From the pressure signal and the direct visualization of the flow with high-speed camera (Fig. 15), it is possible to determine the minimum injection conditions for the positive ignition of the TDW system inside the combustion chamber as a function of the mixture equivalence ratio.

In the case of a positive TDW initiation, the static pressure inside the combustor increases to a much higher level (between 0.810 5 and 1.251 05 Pa) than when no detonation occurs (due to the lack of a geometric throat at the exit of the combustion chamber).

It is found that increasing the specific mass flow rate increases both lean and rich ignition limits of the engine and that it is possible to start a TDW at very low combustion chamber pressure in a wide range of equivalence ratio (0.5–1.7), with a very low amount of energy (less than 1 J) (Fig. 16).

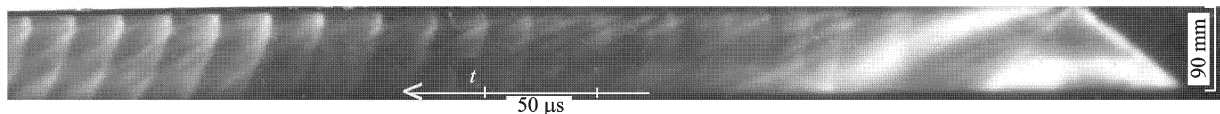


Fig. 15 Visualiation of low ambient pressure ignition phase

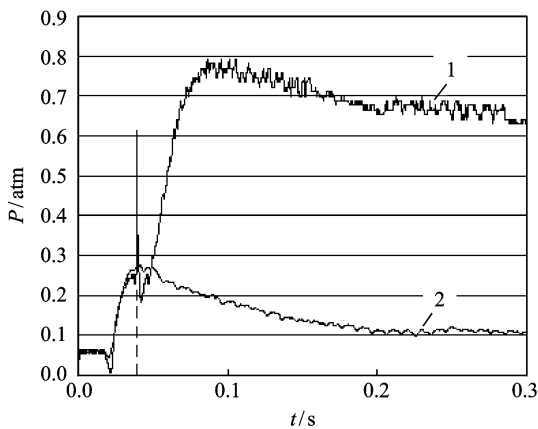


Fig. 16 Two cases of ignition (1) and non-ignition (2)

5 NUMERICAL SIMULATION

With MBDA support, ICARE Lab is developing different levels of numerical simulation to provide, in middle term, needed tools to develop and optimize actual engines. The first approach consisted in performing Euler computation using periodical boundaries conditions^[10]. Even if these computation have still to be refined, they already report the right overall operation and constitute a very good support to better understand the detonation wave self-ignition process (Fig. 17).

Such computation allow also at determining the stream lines into the chamber (in engine axis). Fig. 18 shows that these stream lines are not too much inclined and should not lead to strong skin friction losses.

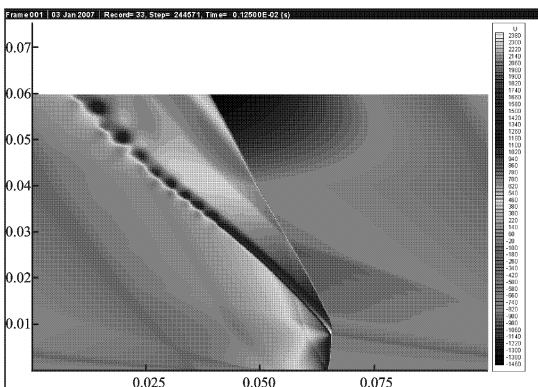


Fig. 17 Example of computation results obtained by ICARE

6 DEMONSTRATION ENGINE

Based on previous studies and the growing

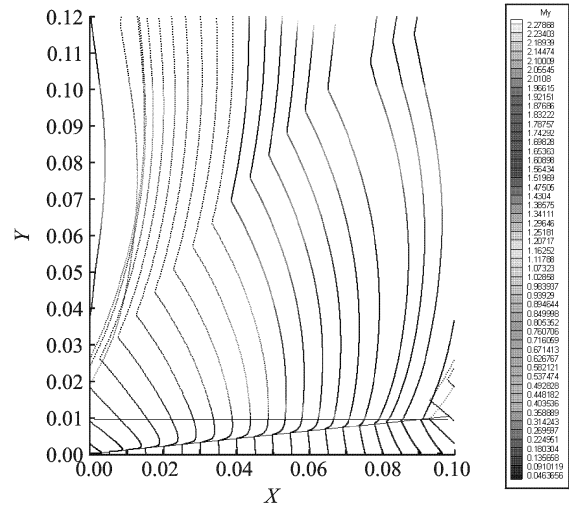


Fig. 18 Trajectory of 20 particles released from top injection wall

potential of such concept, a demonstration engine is designed. This large scale engine (Fig. 19) is to be manufactured and tested in existing test facility. The combustion chamber is 350 mm (external inner diameter) and 280 mm (internal inner diameter) and will be able to operate with GH_2/GO_2 or GH_2/LO_2 or liquid hydrocarbon/air with the change of supply lines and injection wall. This engine mock-up is modular and actively cooled.

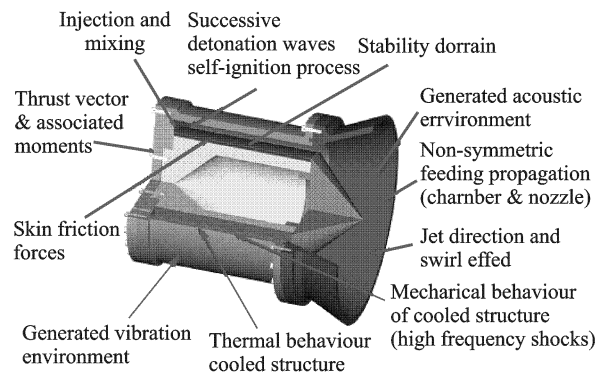


Fig. 19 CDWE demonstration engine

With H_2/O_2 , the injection pressure will be limited (between 1.0 and 1.5 MPa) and resulting mean pressure inside the combustion chamber with the envisioned mass flow rate (between 12 and 15 kg/s, depending on the equivalence ratio) is expected near 0.5 MPa, a value sufficient to deliver several thousands daN of thrust. Moreover, the engine will be equipped with a complete weighing system providing thrust vector compo-

nents and corresponding moments

Thanks to its modularity, the engine will be used, in a first step, as a non-flying workhorse allowing to address all the key points such as :

- (1) Effect of injection configuration and conditions (2-phases mixing);
- (2) Stable operation domain and key influencing parameters;
- (3) Thermal and mechanical strength of the combustion wall (fuel-cooled structure, high frequency mechanical shocks);
- (4) Effect of disymmetric injection on thrust vectoring when including a full nozzle;
- (5) Generated environment (vibration and acoustics).

In the second step, the modularity will allow to progressively replace all the engine components by flight-worthy ones in order to finally obtain a flight-worthy demonstrator which will be tested to really assess the achievable performance when taking into account all the technology issues.

As a first step in the development of this demonstrator, and with the support of EADS Group, MBDA designs and manufactures a preliminary small scale demo based on works done with Lavrentiev Institute (Fig. 20). This 100 mm diameter mock-up is under testing within MBDA Bourges Subdray test facility. In the first step, the small scale demo is tested with pure hydrogen. Then, a mixture of methane and hydrogen will be used. Test duration is about 3 to 4 s.

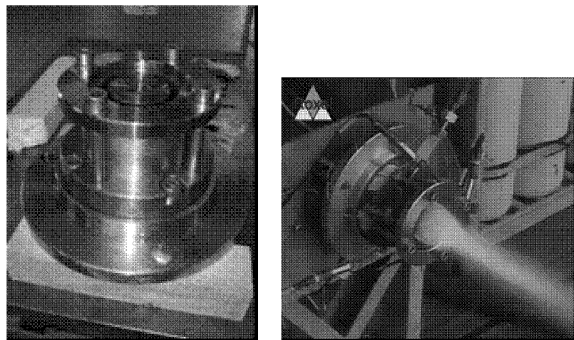


Fig. 20 Small scale preliminary demo under testing

7 CONCLUSION

MBDA has been leading R&T works in coop-

eration with the Lavrentyev Institute of Hydrodynamics on the Continuous Detonation Wave Engine.

The mixtures used in the different experiments are mainly GH_2 & LO_2 or LHC & GO_2 . The goals of those experiments are to address some key technology points in order to be able to evaluate the global interest of an engine using TDW for the combustion process. It is found that such engine could deliver impressive thrust in a very small package (275 daN for internal diameter of 50 mm and length of 100 mm, kerosene-oxygen engine) and that could be increased with the use of a diverging nozzle.

Due to the geometry of the combustion chamber, a plug or aerospike nozzle seems to be the best design, the thrust vectoring capability of this engine (with the local change of the mass flow rate) being a way to solve the problem of attitude control.

The heat fluxes are very high but located mostly near the injection wall. This point will help the gasification of the liquid component injected inside the combustion chamber. The transverse flow velocity could also help the mixing of the fresh products, but also the mixing of the fresh mixture with the detonation products.

Some preliminary tests are performed to evaluate the capability of C/SiC composite materials to sustain the very severe mechanical environment generated by the rotating detonation waves. Beyond these first steps, a full scale demonstrator is designed and should be developed in 2010 allowing a large set of test from basic experiment to improve knowledge and understanding of the TDW process to technology demonstration test including fuel-cooled structure validation. By waiting, a small scale preliminary demo is designed and manufactured and will be tested in Spring 2010.

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法国 MBDA 爆震和连续爆震波发动机的研发

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摘要:连续爆震波发动机(CDWE)可以弱化一般爆震发动机(PDE)对环境条件的要求,尤其是初始条件要求弱化简化了发动机结构。为了探讨 CDWE 用于空间发射器的可行性, MBDA 与 Lavrentiev 学院联合进行了一些试验,研究了其工作模式和一些关键点。结果发现:这种发动机在非常小的装置中可提供可观的推力(275 daN, 条件:直径 50 mm, 长 100 mm, 航空煤油加氧气)。如果采用扩张型喷管,推力还可能增加。在现有尺寸下,插入式或气动锥喷管似乎是最佳设计,在同一流量下,发动机的矢量能力是解决姿态控制的一个方法。热流量非常大,但主要集中在喷射壁

面,这一点将有助于在燃烧室内气化喷入的液体燃料。另外,做了初步试验来评估 C/SiC 复合材料在转动爆震波非常恶劣的机械环境下的性能。在这些研究以外, MBDA 还设计了大尺寸地面实验装置来研究使用 LH₂/LO_x 混合物的连续爆震波发动机的所有相关问题。作为大尺寸研发的第一步,小尺寸的演示在 2010 年春季进行。

关键词:爆震波发动机; 推进; 性能模型

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