R&T EFFORT ON CONTINUOUS DETONATION WAVE ENGINES

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ABSTRACT

Due to its thermodynamic cycle, the pulsed detonation engine (PDE) has theoretically a higher performance than classical iso-pressure combustion propulsion concepts. Nevertheless, PDE design must avoid this advantage being not fully compensated by the difficulties encountered for practical use of the PDE concept or by the complex technology, which could be needed to implement it in an operational flying system, particularly due to severe generated vibration environment. After experimental and theoretical studies led in cooperation with French and Russian research institutes, MBDA is now leading a cooperation with Singaporean DSO to develop an actual PDEngine which could be flight tested within a few years.
The Continuous Detonation Wave Engine (CDWE) can also be considered to reduce the environmental conditions generated by PDE while reducing the importance of initiation issue and simplifying some integration aspects. Specific experimental program has been performed by MBDA and Lavrentiev Institute to understand unsteady, three dimensional flow behind the detonation wave and to address some key points for the feasibility of an operational rotating wave engine for space launcher. On the basis of these results, a preliminary design of an operational engine has been performed by taking into account all engine/airframe integration issues in order to optimize the benefit of detonation wave engine. Beyond these first steps, MBDA designed a large scale ground demonstrator allowing to address all issues for a continuous detonation rocket engine using LH2/LOx mixture. As a first step toward the development of this large scale engine, a small scale demo is to be tested in Fall 2009.

INTRODUCTION

During past years, MBDA performed some theoretical and experimental works, mainly in cooperation with LCD laboratory at ENSMA Poitiers, on Pulsed Detonation Engine (PDE). These studies aimed at obtaining a preliminary demonstration of the feasibility of the PDE in both rocket and airbreathing modes and at verifying the interest of such a 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, the pulsed detonation engine (PDE) has theoretically a higher performance than an other 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 the PDE concept or by the complex technology, which could be needed to implement it in an operational flying system.

Indeed, PDE performance is driven by the following parameters:

- quality of the pre-mixing,
- value and nature of the needed energy for igniting the detonation,
- duration of the high pressure level (depending of the filling coefficient),
- 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, a PDE a priori 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 Singaporean 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 the PDE. That generally leads to complex arrangements, needed 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 :

- well known existing propulsion systems(rockets,turbojets,ramjets) have already high performances and are still being improved,
- 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 the 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 correspond 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 to a Pulsed Detonation Engine, 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 since a long time, particularly at LIH (Lavrentiev Institute for Hydrodynamics) in Novosibirsk. As it was done for PDE, specific experimental program has been performed by MBDA and Lavrentiev Institute to understand unsteady, three dimensional flow behind the detonation wave and to address some key points for the feasibility of an operational rotating wave engine for space launcher :

- two-phase mixture detonation,
- operating limits (injection pressure for example),
- noise generated by a CDWE operating at several kilohertz,
- heat fluxes (intensity, areas) and cooling strategies,
- composite materials (Carbon / Silicon Carbide) compatibility,
- engine thrust vectoring capability.

On the basis of these results, a preliminary design of an operational engine has been 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 have been performed to address some key points like thrust vectoring, heat fluxes and material compatibility, operation in low pressure environment [4] to [6]. In parallel, a dedicated effort has been 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 LH_2/LO_x mixture.

CDWE OVERVIEW AND GENERALITIES

The main feature of a CDWE is an annular combustion chamber closed on one side (and where the fuel injection take place) and opened at the other end. Inside this chamber, one or more detonation waves propagate normally to the direction of injection (Fig. *1*).

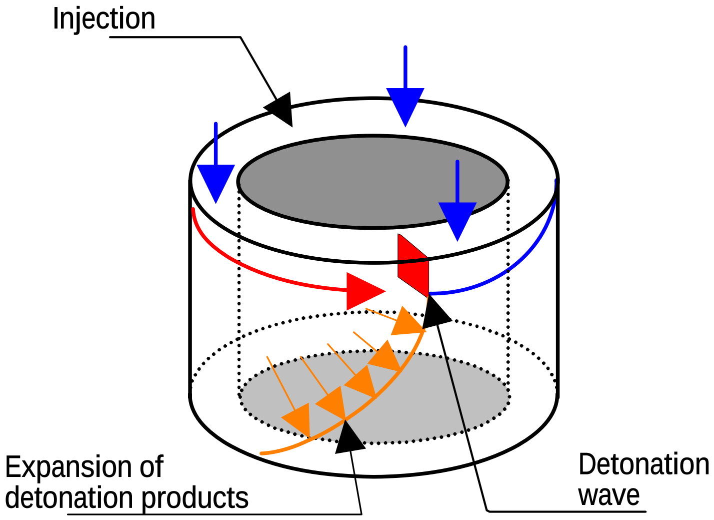
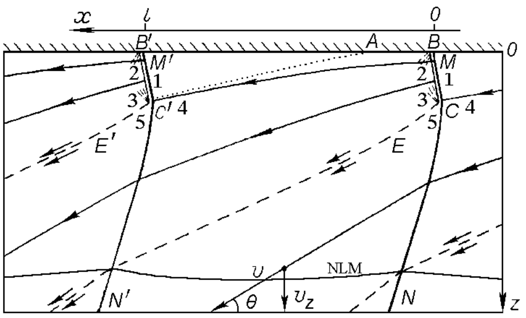


Fig. 1 – CDWE principle

In fact a CDWE is very close to a multitube PDE (Pulse Detonation Engine) cluster running globally at very high frequency (typically several kHz) and so the mean pressure inside the chamber is higher than for a typical single tube PDE (as is the mean thrust per unit area). If for a PDE the injection pressure could be as low as the ambient pressure, in the case of a 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 2D 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 transform 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 the 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.



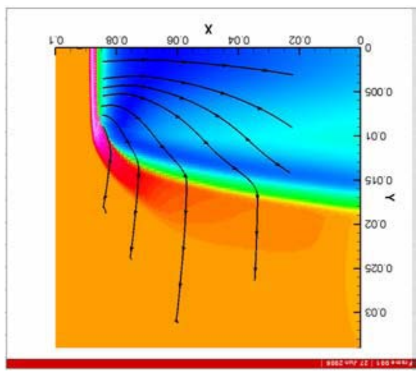


Fig.2 – Flow field in TD Wave reference axis *Fig.3 – Flow field in laboratory reference axis*

SYSTEM STUDY AND ENGINE SIZING

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

It was 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 H2-O2 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), the CDWE will have a slightly increased design flexibility than a conventional LRE, with the possibility 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 a LRE. But we can also use reduced feeding pressure (here 2.2 MPa instead 7.0 MPa) with still interesting performances as shown by Table 1.

Table 1 – comparison of achievable performance

d_n, (m)	S_n/S_1	p_n/p	v_n/v_z	I, sec	I^*, sec	J, (kN)	J^*,(kN)	$\Delta J/J^*$
0.4	1.333	0.6337	1.10	326	296	107.97	98.01	0.101
1.1	10.08	0.0399	1.486	396	383	131.10	126.73	0.034
2.15	38.5	0.0073	1.623	424	415	140.06	137.05	0.022

*(Figures with * are related to reference LRE – ER = 1)*

This difference between the CDWE and the LRE vaccum performance decreases as nozzle exit size increases (expansion rate being more limited for a same detonable mixture mass flow).

Moreover, the integration of a CDWRE can be very attractive when considering an aerospike configuration as it is shown by fig.4. Such system would be particularly well adapted to power the fully axisymmetric airbreathing space launcher proposed by MBDA [0] Fig.5).

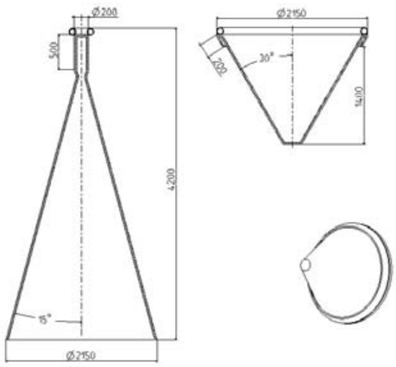


Fig. 4 – comparison between CDWE and equivalent classical LRE

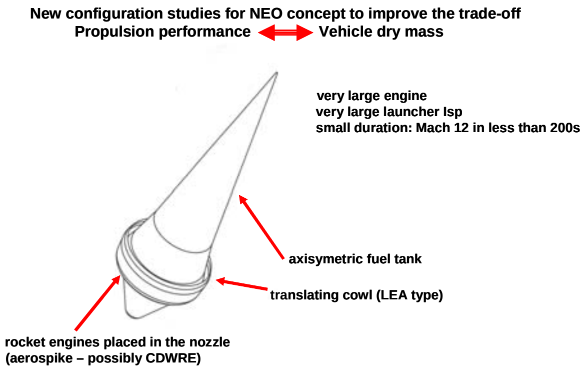


Fig.5 – Fully axisymmetric airbreathing space space launcher NEO

In order to better assess the real interest of the CDWE for space launcher application, some specific action is led to develop a global performance design tool. A first step consisted to adapt the model propose by LIH. Today, ICARE Lab is developing a more accurate model and first results are provided by [8]. Application of this model to the case of H2/O2 mixture allow to assess achievable performances (Fig. 6)

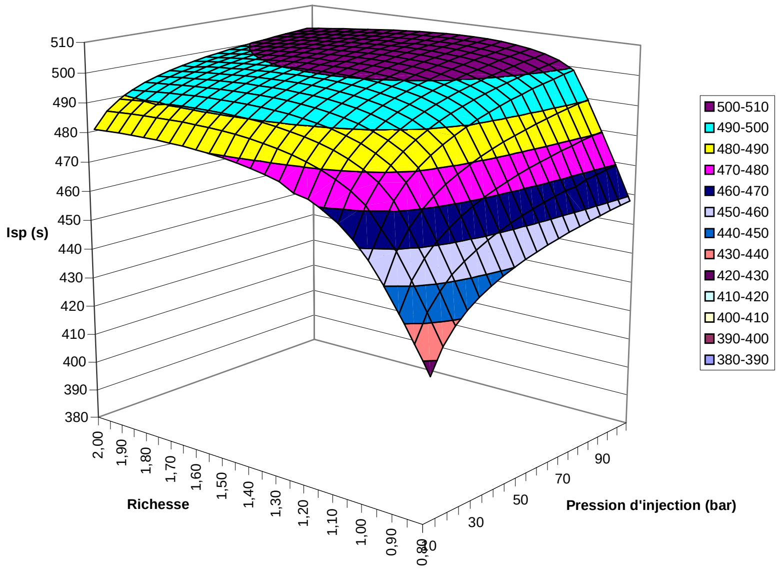


Fig. 6 – Achievable performance for a H2/O2 Continuous Detonation Wave Rocket Engine

EXPERIMENTAL WORKS

Using the mock-up design principle described by Fig.7 and the test bench shown in Fig.8, some basic experiments have been first performed with LIH, taking advantage of their long experience on such a test:

- experiments in Combustion Chamber (CC) with inner diameter of 50mm, 100mm and 280mm,
- homogeneous (gas / gas) and heterogeneous (liquid / gas) mixture studied.

The experimental detonation chamber is fed with fuel and oxydizer supplied by pressurised tanks blow-down. Due to this, the test duration is limited (< 1s) and the test conditions are rapidly changing during the test run (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). AT the contrary, it provides a large variation of pressures and equivalence ratio, which allow proving the stability of the detonation process over a large range of feeding conditions.

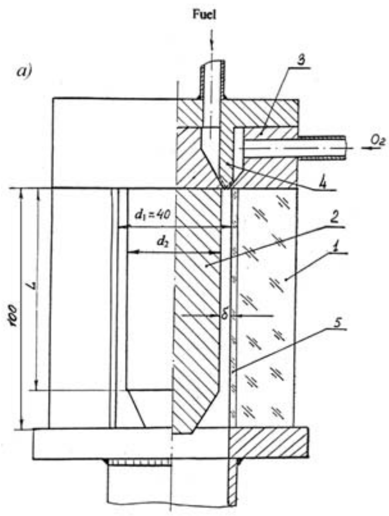


Fig.7 - Mock-up design principle

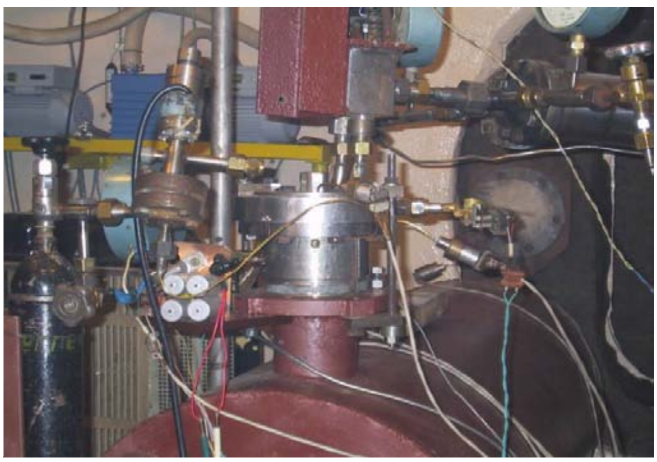


Fig.8 – General view of test bench at LIH

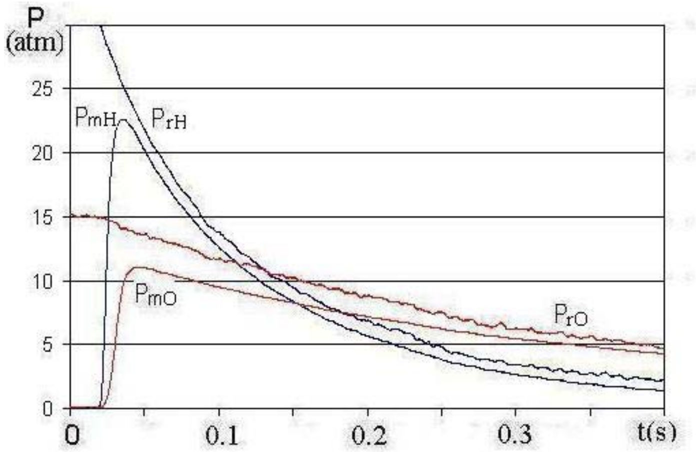


Fig.9 – Typical feeding conditions evolution during a test run

Some main obtained results are:

- detonation regime obtained in 100 mm diameter CC with GH2/LOx,
- detonation regime obtained in 330 mm diameter CC with kerosene/air,
- high thrust density achieved in small CC (275 daN for a 50 mm inner diameter kerosene/GO2 engine).

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

- the height of the fresh mixture layer h is a function of the detonation cell size,
- the frequency of the engine is given by the ratio D/l, where D is the detonation velocity and l the distance between two consecutives 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.

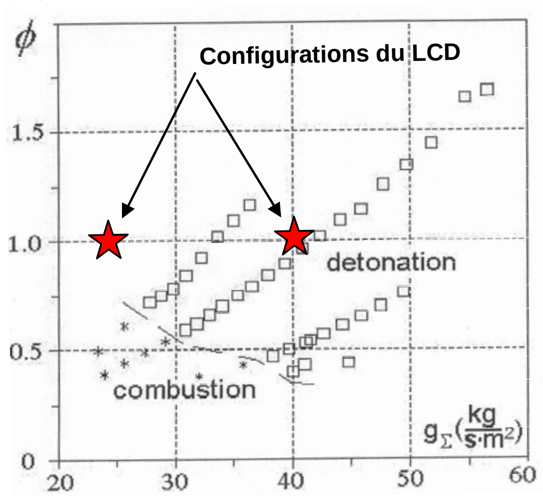


Fig.10 –Stability domain - gaseous H2/O2 mixture

In this particular case, it has to be underlined that the detonation waves speed is 2770m/s at equivalence ratio 1 when Chapman-Jouguet speed Dcj is 2840m/s. But equivalent results can be obtained (depending of the injection configuration) with other mixtures as shown in Table 2.

Fuel	Propane/O_2 (gas)	H2(gas)/O2(liquid)	Kerosene/O_2 (gas)	Kerosene/ O_2 (liquid)	
ϕ	1.0	1.7	0.92	1.22	0.95
D, m/s	**2270**	**3076**	**2000**	**2460**	**2200**
Dcj, m/s	**2430**	**3170**	**2360**	**2520**	**2400**
Delta (%)	6,6 %	3,3 %	15,2 %	2,3 %	8,3 %
G (kg/s/m²)	**140**		**106**	**707**	**1450**

Table 2 – example of detonation wave speed compared with corresponding Dcj

SPECIFIC ISSUES

Thrust vectoring capability

One of the peculiarities of a 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 effect could be explained with the assumption that behind a TDW (and between two consecutive TWD), there is a complex series of shock waves. If we increase the mass flow rate, 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 occurs and a new TDW appears. If we decrease the mass flow rate inside the combustion chamber, the height of the fresh mixture between two consecutive TDW decreases and could be not sufficient to support a shock-induced combustion and the TWD degenerates into a more simple shock wave.

This self-adaptation of the detonation to the fresh mixture local mass flow made it possible to gain thrust vectoring with the local increase of the mass flow. Some experiments were 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 was changed in one half of the engine compared to the other half. In another series, the injectors diameter was increased in order to double the local mass flow rate in one half of the engine.

Eight pressure probes (P1 to P8) were located along the circumference of the outer wall of the annular chamber.

In all experiments it was possible to obtain an increase of the thrust on one side of the engine. The most promising experiments shows that a 30 % increase of the thrust-wall overpressure was possible if we double the mass flow rate. This increase is lower than expected but the small diameter of the test engine limited the heterogeneity of the flow inside the combustion chamber. With a larger engine, a 100% increase of the thrust on one side (compared to the other side) should be possible (Fig.11).

We found also that there was a small shift of the maximum and minimum pressure values. Those extreme value seems to be located between P7 and P8 (for the maximum) and between P3 and P4 (for the minimum) instead of directly near P1 and P5.

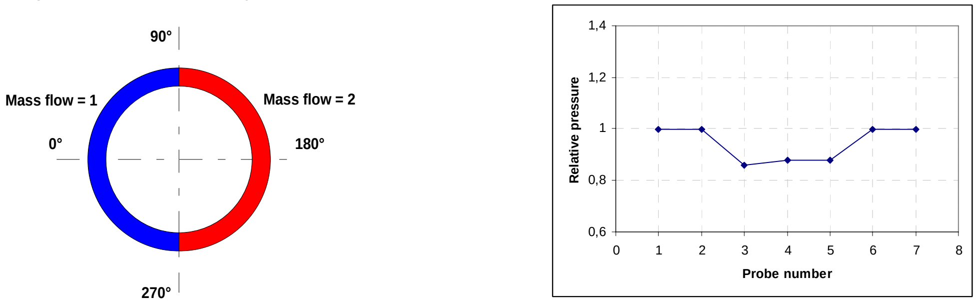


Fig. 11 – Pressure evolution along the chamber circumference

Compared to a LRE (with a gimbaled 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.

Heat fluxes and cooling system

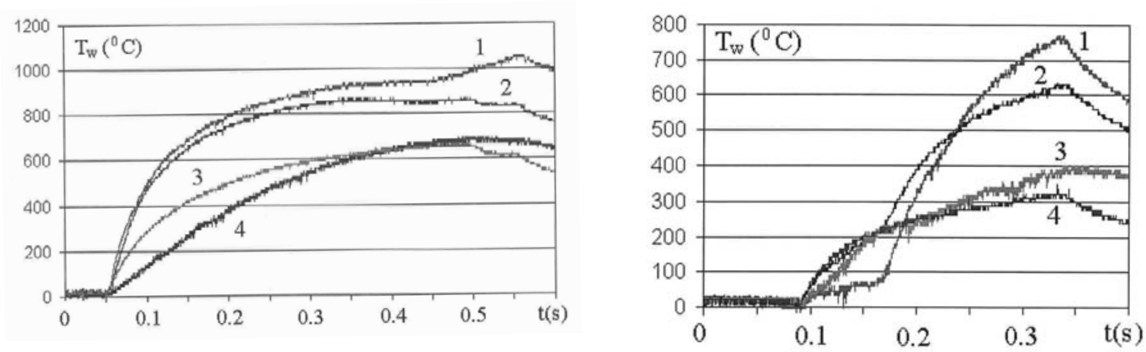
Due to the transverse velocity of the flow behind the detonation wave (several hundreds of meter per second), the highest heat load inside the CC occurs near the thrust wall and decreases along the axial axis.

Wall temperatures in heat-sink combustion chambers were recorded with Hydrogen/Oxygen and kerosene/Oxygen mixtures (Fig. 12).

The cooling system design could be critical because for metallic structures the mean heat fluxes near the thrust wall were measured between 12 MW.m-2 and 17 MW.m-2 with local values even higher (with Hydrogen/Oxygen mixture).

This heat flux repartition is also very different from the one obtained in a 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.

The high heat fluxes anticipated in a CDWRE lead to the issue of active cooling, a very difficult task with metallic structures with a wall temperature limited to the vicinity of 1000 K.



Kerosene/Oxygen

Hydrogen/Oxygen

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

Composite materials could achieve higher wall temperature (up to 1800 K) even in oxidizing conditions. After a careful review of existing products, some C/SiC composite materials were 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 series a dozen of short duration (0.5 s) tests without apparent damage to the material surface (Fig.13 & 14). A new test series has then been performed with more severe conditions (feeding pressure up to 2.5 MPa) during which the two samples have been damaged proving that this point is surely one key technology issue to be carefully addressed in the future.

Fig. 13 - The two composite parts *Fig.14 - part installed on chamber central body*

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 was investigated using LIH 100 mm ID detonation chamber connected to a 0.5 m^3 vacuum tank with an initial pressure of 0.06 10^5 Pa.

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

Blasting copper wires were 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 were selected for those experiments and injection pressure between 1.6 10^5 and 25 10^5 Pa (for hydrogen), and 5 10^5 Pa and 11 10^5 Pa (for oxygen) allowed the investigation of ignition within a wide range of low specific mass flow (between 21 $kg.s^{-1}.m^{-2}$ and 57 $kg.s^{-1}.m^{-2}$). This mass flow rate is ten times lower than mass flow used in previous experiments but was 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 was 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 0.8 105 Pa and 1.25 105 Pa) than when no detonation occurs (due to the lack of a geometric throat at the exit of the combustion chamber).

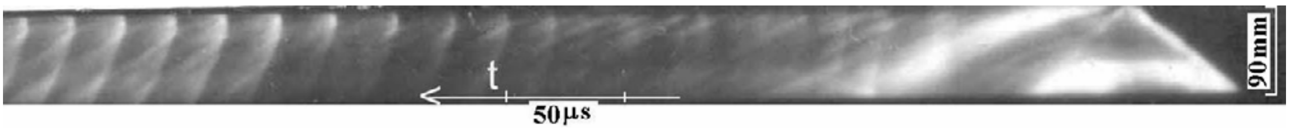


Fig. 15 – visualiation of low ambiant pressure ignition phase

It was found that increasing the specific mass flow rate increases both lean and rich ignition limits of the engine and that it was 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).

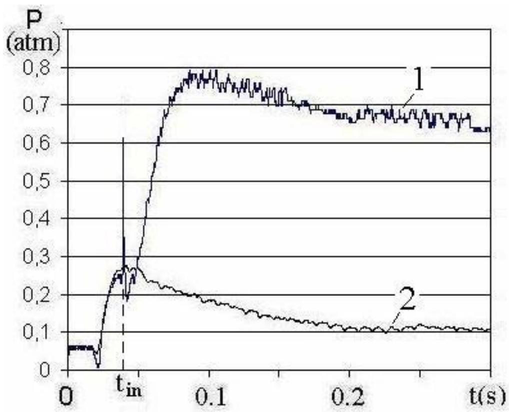
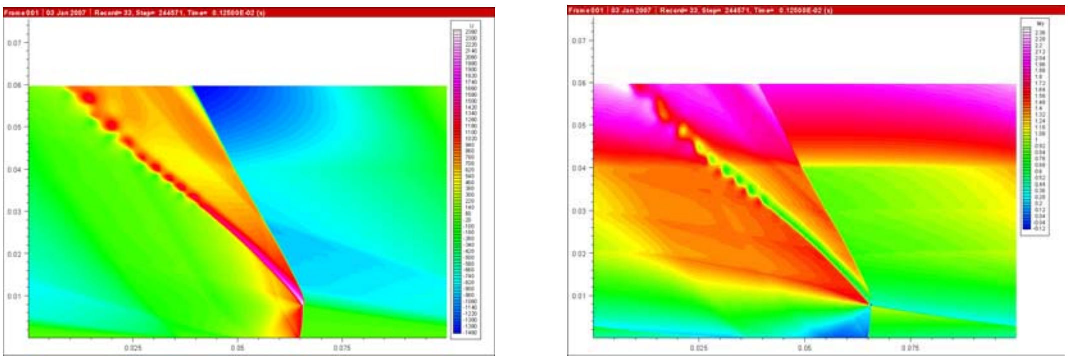


Fig.16 – Two cases of ignition (1) and non-ignition (2)

NUMERICAL SIMULATIONS

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 [9]. 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 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.



Circumferential speed Axial Mach number

Fig.17 – example of computation results obtained by ICARE Lab

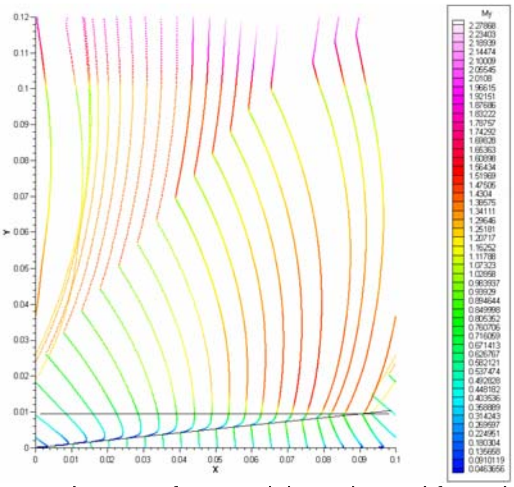


Fig. 18 – Trajectory of 20 particles released from the top injection wall

DEMONSTRATION ENGINE

Based on previous studies and the growing potential of such concept, a demonstration engine has been 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.

With H_2/O_2, the injection pressure will be limited (between 1 MPa and 1.5 MPa) and resulting mean pressure inside the combustion chamber with the envisioned mass flow rate (between 12 $kg.s^{-1}$ and 15 $kg.s^{-1}$, depending on the equivalence ratio) is expected near 0.5 MPa, a value sufficient to deliver several thousands daN of thrust.

The injection wall is divided in 8 sectors in order to be able to change the local mass flow rate and investigate the thrust vectoring effect with a diverging nozzle or with a center core nozzle (aerospike). Moreover, the engine will be equipped with a complete weighing system providing thrust vector components and corresponding moments.

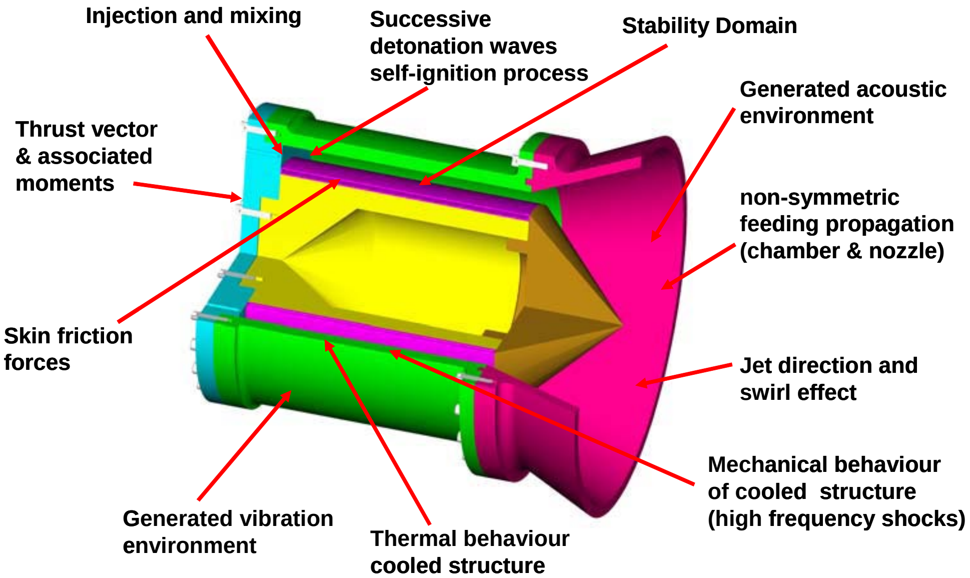


Fig.19 - CDWE demonstration engine

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 :

- effect of injection configuration and conditions (2-phases mixing),
- stable operation domain and key parameters influencing it,
- effects of high speed tangential flow (skin friction and heat fluxes),
- thermal and mechanical strength of the combustion wall (fuel-cooled structure, high frequency mechanical shocks),
- effect of dissymmetric injection on thrust vectoring when including a full nozzle,
- generated environment (vibration and acoustics),
- …

In a 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 designed and manufactured a preliminary small scale demo based on works done with Lavrentiev Institute (Fig. 20).

This mock-up has an external diameter of 100mm and is to be tested in Fall 2009 within MBDA/ROXEL Bourges Subdray test facility.

In a first step, the small scale demo will be tested with pure hydrogen. Then, a mixture of methane and hydrogen will be used.

Test duration will be step by step increased from 0.5 to 2-3 seconds while a simple direct thrust measurement will be evaluated.

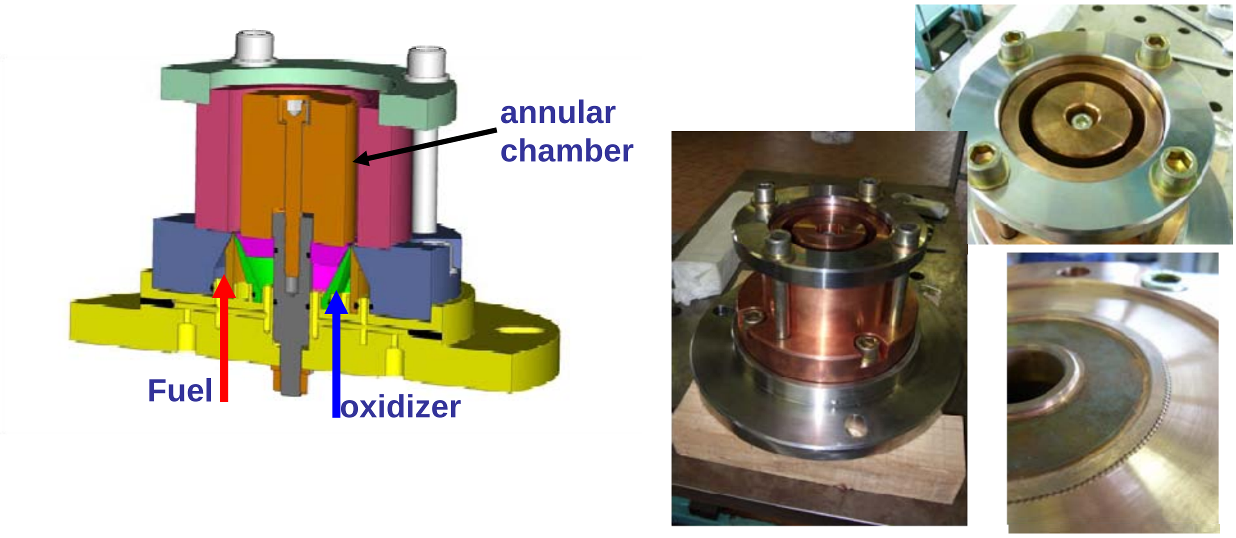


Fig.20 – Small scale preliminary demo to be tested in Fall 2009

CONCLUSION

Since a few years, MBDA leads R&T works in cooperation with the Lavrentyev Institute of Hydrodynamics on the Continuous Detonation Wave Engine.

The mixtures used in the different experiments were mainly $GH_2 – LO_2$ or $LHC – GO_2$. The goals of those experiments were 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 was found that such engine could deliver impressive thrust in a very small package (275 daN for a 50 mm (internal diameter) and 100 mm long, 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 have been 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 has been designed and should be developed in 2009 allowing a large set of test from basic experiment to improve knowledge and understanding of the TDW process to technology demonstartion test including fuel-cooled structure validation.

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REFERENCES

1. E.DANIAU, R.ZITOUN, C.COUQUET, D.DESBORDES
   "Effetcs of Nozzles of Different Length and Shape on the Propulsion Performance of Pulsed Detonation Engines", High-Speed Deflagration and Detonation. - Moscow: Elex-KM Publishers, 2000), pp. 251-262
2. E. DANIAU, F. FALEMPIN, G. ZHANG, H.S.FOO, M.S. YIP, T.Y.JIANG, D.B. LIU
   Preliminary work for a pulsed detonation engine demonstrator - AIAA-2006-7957
3. G. ZHANG, Y. T. Jiang, H. S. FOO, M. S. YIP, F. FALEMPIN, E. DANIAU
   First steps for the development and testing of a Pulse Detonation Engine for UAV application - AIAA-2008-2681
4. E. DANIAU, F. FALEMPIN, S. ZHDAN, F. BYKOVSKIY
   Detonation Wave Propulsion Systems : First Step Toward Operational Engines - ISABE – 2005 – 1302
5. E. DANIAU, F. FALEMPIN, F.A. BYKOVSKII, S. ZHDAN
   Pulsed and Rotating Detonation Propulsion System: First Step Toward Operational Engines - AIAA 2005-3233
6. F. FALEMPIN, E.DANIAU, N.GETIN, F.A.BYKOVSKII, S.ZHDAN
   Toward a Continuous Detonation Wave Rocket Engine Demonstrator AIAA-2006-7956
7. F. FALEMPIN, M. BOUCHEZ
   Fully axisymmetric airbreather concept for space Launcher – first application to a micro space launcher - IAC-08-C4.5.6
8. D. M. DAVIDENKO, I. GOKALP, A. N.KUDRYAVTSEV
   AIAA-2008-2680
9. D. M. DAVIDENKO, F. JOUOT, A. N. KUDRYAVTSEV, G. DUPPRE, I. GOKALP, E.DANIAU, F.FALEMPIN
   Continuous detonation wave engine studies for space application - 2nd EUCASS – Brussels – July 2007

