Continuous Detonation Wave Engine

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Detonation wave engines, thanks to their more efficient thermodynamic properties, are expected to exhibit a higher level of performance than more conventional propulsion system that rely on constant-pressure combustion processes. Nevertheless, it still has to be proved that this advantage is not superseded by the difficulties which could be encountered to practically define a real engine and to implement it in an operational flying system. In that respect, continuous detonation wave principle appears less challenging than the pulsed detonation process and should lead to the development of more efficient propulsion systems, even if such radical adaptation of the overall engine concept and of the vehicle architecture would be necessary. During past years, MBDA performed some theoretical and experimental works, mainly in cooperation with the Lavrentyev Institute of Hydrodynamics in Novosibirsk. These studies aimed at obtaining a preliminary demonstration of the feasibility of a Continuous Detonation Wave Engine for air-breathing and rocket application. 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. Those studies were focused on global performance and understanding of the unsteady, three dimensional flow behind the detonation wave. On the basis of these results, a preliminary design of an operational Continuous Detonation Wave Rocket Engine usable for the upper stage of a space launcher has been performed taking into account all engine/airframe integration issues in order to optimize the benefit of detonation wave engine. Then, specific experimental works have been undertaken to address some key issues like noise generated by a Continuous Detonation Wave Engine operating at several kHz, heat fluxes (intensity, areas) and cooling strategies, composite materials (Carbon / Silicon Carbide) compatibility, engine thrust vectoring capability. Those results were used to validate 1-D and 2-D unsteady computations. Beyond these first steps, a full scale demonstrator has been designed and should be tested within the next years.

NOMENCLATURE

CC	=	Combustion Chamber
CDWE	=	Continuous Detonation Wave Engine
CD	=	Continuous Detonation
PDE	=	Pulse Detonation Engine
TDW	=	Transverse Detonation Wave
h	=	height of the fresh mixture layer before detonation
h^*	=	minimum height of the fresh mixture to support a detonation
L	=	combustion chamber length
l	=	distance between two consecutive detonation waves
θ	=	exit angle of the flow
d_1	=	combustion chamber inside diameter
d_2	=	center-body diameter
δ	=	combustion chamber width
S_{inj}	=	injection area

INTRODUCTION

Due to its thermodynamic cycle, a detonation wave engine has theoretically a higher performance than a classical propulsion concept using the combustion process. Nevertheless, it still has to be proven that this advantage is not compensated by the difficulties which could be encountered to practically define a real engine and to implement it in an operational flying system.

Ya. Zel'dovich[1] was the first investigator who considered the theoretical problem of a detonation mode for the combustion of fuel. He showed that detonation regime of combustion at the same initial state is more useful than the deflagration because of the lower entropy of reaction products in the case of detonation. He also stated that a practical attempt to use detonation processes was very difficult and that decisive factors like simplicity of implementation and reduction of losses in a continuously operating machine were in favor of constant-pressure combustion devices.

This comment was very sensible in 1940, but now, after more than 65 years of research and improvements, constant-pressure combustion devices have reached a point were any performance increase will be limited and costly, so some efforts should be devoted to the study of other devices that could deliver increased performances or reduce the complexity, weight or cost.

J.A. Nicholls, E.K. Dabora and R.A. Gealler realized the combustion of fuel in stationary compression shock waves originating near the exit of supersonic jet to the atmosphere[2].

During the last ten decade, the renewal of the interest for Pulsed Detonation Engine (PDE) led to the performance of a lot of dedicated R&T programs and a first flight test program performed by AFRL[3].

In that context, MBDA France performed some theoretical and experimental works on Pulsed Detonation Engine (PDE), mainly in cooperation with LCD laboratory at ENSMA Poitiers. These studies aimed at obtaining a preliminary demonstration of the feasibility of the PDE in both rocket and air breathing modes and at verifying the interest of such a PDE for operational application. Further studies are still in progress with CIAM and Semenov Institute in Moscow.

On this basis, several engine concepts have been studied and evaluated at preliminary design level, for both space launcher and missile application. Today, the effort is focused on the development of a small caliber air breathing engine able to power a UAV with very demanding requirements in terms of thrust range.

B.V. Voitsekhovskii proposed an alternative method of realization of continuous detonation. He used the analogy with the process of running wave occurring in the case of spin-detonation propagation in a round tube[4][5]. In both cases the burning of the mixture is achieved in a transversal detonation wave (TDW) moving normally from the main direction of the combustion products. During ordinary spin detonation, transversal detonation wave propagates along the forward shock front in a spiraling trajectory relatively to the tube and burns a shock-compressed mixture. The concept of the Continuous Detonation Wave Engine (CDWE) has been extensively studied during the last decades at the Lavrentyev Institute of Hydrodynamics (LIH).

The use of such a CDWE can be considered to reduce the environmental conditions generated by PDE while reducing the importance of initiation issue and simplifying some integration aspects. As it was done for PDE, MBDA France is leading a specific R&T program, including basic studies led with the Lavrentiev Institute of Novosibirsk, to assess some key points for the feasibility of an operational Continuous Detonation Wave Rocket Engine (CDWRE) for space launcher.

But, continuous detonation wave can have also other application for turbojets and for ramjets. In order to address all these possible applications, a ground demonstrator has been designed and should be developed

and tested within the next years within the framework of the National Research & Technology Center (CNRT) "Propulsion for Future" located in Orleans/Bourges region.

CDWE OVERVIEW AND GENERALITIES

The main difference between a deflagration and a detonation is linked to the mechanism of the flame propagation. In a deflagration, the flame propagation if a function of the heat transfer from the reactive zone to the fresh mixture (generally conduction). The detonation is a shock induced flame, resulting in the coupling of a reaction zone and a shock wave. The shock wave compress and heat the fresh mixture, bringing it above its self-ignition point. On the other side, the energy released by the flame contributes to the propagation of the shock wave.

The main feature of a 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 (Figure 1).
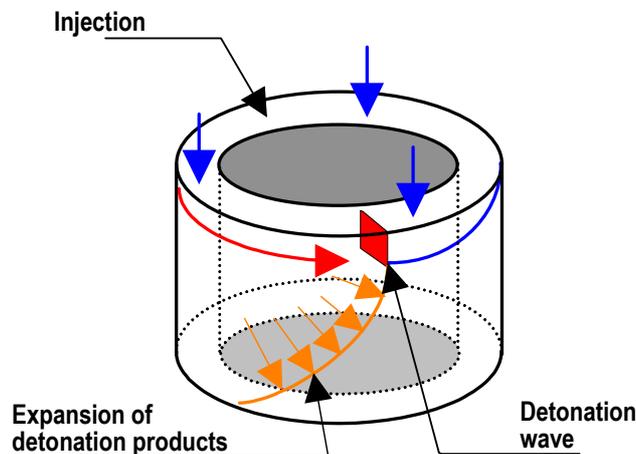

Figure 1. Simplified diagram of a CDWE combustion chamber.

In fact a CDWE is very close to a CDWE is very close to an infinite number of small PDE globally running at very high frequency (typically several kHz) and dephased and so the mean pressure inside the chamber is higher than for a typical PDE. 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 better suited for rocket operation than for air-breathing operation if no air pre-compression is provided.

The flow inside this chamber is very heterogeneous, with a 2D expansion fan behind the leading shock (Figure 2). The transverse detonation wave (BC and B'C') propagates in a small layer of fresh mixture (AB') near the injection wall. 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 realisation of CD in small chambers.
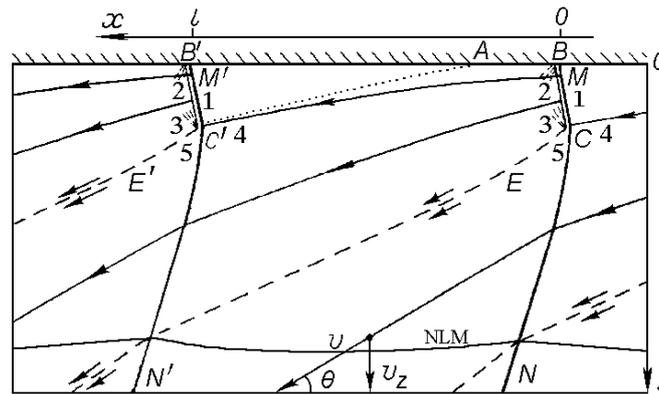
Figure 2. Structure of the flow inside the combustion chamber.

The detonation velocity observed in the reference laboratory is generally less than the Chapman – Jouguet detonation velocity. Several explanations could be given to this phenomenon:

- due to the very small time between two detonation waves, the mixing is less than ideal and the detonation characteristics could be changed,

- the fresh gases could partially mix with the detonation products and do not react,

- due to the expansion fan behind a detonation wave and the speed of the flow, the fresh mixture gain some speed in the X direction, so the detonation propagates in counter-flowing fresh mixture.

With this singular flow structure, this kind of engine possesses some unique characteristics:

- during the expansion, the flow velocity on the X axis changes direction from –X (just after the detonation wave) to +X (Figure 2),

- the flow velocity on the Z axis exhibits a transition from subsonic to supersonic inside the constant section duct, through a neutral line of Mach (NLM),

- there is no need for a geometric throat at the end of the combustion chamber,

- the flow exit the combustion chamber at the velocity v with an angle θ.

The pressure ratio across the detonation front is typically 10, a value lower than the Chapman – Jouguet detonation wave pressure ratio characteristic (18 for hydrogen – oxygen mixture, and higher than 30 for a hydrocarbon –oxygen mixture).

The first application for CDWE is the rocket mode (CDWRE) for which continuous detonation process can lead to a compact and very efficient system enabling lower feeding pressure and thrust vectoring with very attracting integration capability for axi-symmetrical vehicles. But, the CDWE could also be applied to simplified Ramjet Engine with short ram-combustor and possible operating from Mach 0+ without integral booster or to Turbojet with improved performances or simplified compression system (lower compression ratio required).

BASIC EXPERIMENTS

Using the mock-up design principle described by Figure 3, some basic experiments have been first performed with the Lavrentiev Institute:

- experiments performed in CC with inner diameter of 50 mm, 100 mm and 280 mm,

- homogeneous (gas / gas) and heterogeneous (liquid / gas) mixture studied,

- 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).
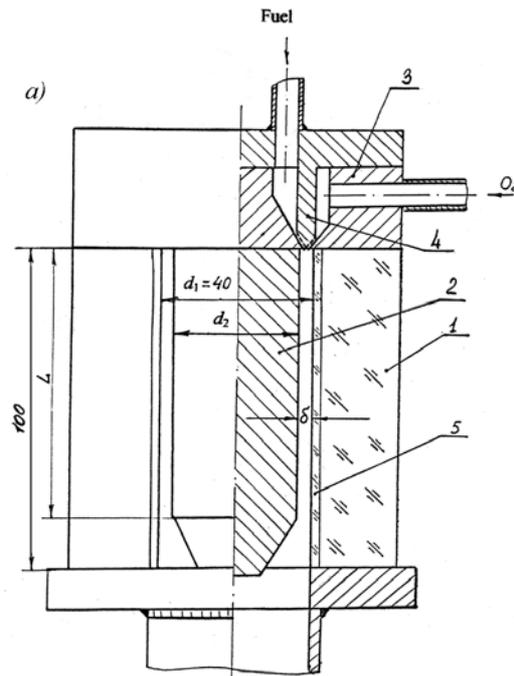

Figure 3. Mock-up design principle

From these experiments, some key points can 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.

PERFORMANCE MODEL

Based on its extensive knowledge, the Lavrentyev Institute of Hydrodynamics developed an analytical model of such engine performance.

The main hypotheses are:

- the wall heat losses are negligible,

- the detonation is a self-sustaining CJ wave,

- the region in front of the wave is called "1", and the region behind the wave is called "2",

- the pressure P_2 is the maximum pressure inside the CC,

- the flow outside region 2 is supersonic everywhere relative to the TDW, except in the front wave (not analyzed) and maybe in the small domain 5 behind the oblique shock wave CN near the point C.

This model will not be detailed here and only the main parameters needed for the sizing of the engine are reported. They are:

- h, the height of the TDW,

- k, the flow mass fraction going thru MC'

- $h_1 = (1-k)h$, the "effective" height of the TDW,

- $\alpha = \dfrac{p_x}{p_z}$, the ratio of the mean pressure acting along MC',

- $\eta = \dfrac{h_1}{l}$, the aspect ratio of the TDW,

- θ_1, the inclination of the streamlines.

Calculations have been done for H_2-O_2 stoichiometric mixture (Table 1) for η and θ_1 values directly found from experiments.

Table 1. specific impulse of stoichiometric H_2-O_2 mixture in a CDWE (without nozzle).

α	$\dfrac{\rho}{\rho_2}$	$\dfrac{p}{p_2}$	$\dfrac{D}{\sqrt{2I_T}}$	θ, deg.	M_z	i,(km/s)	I,(sec)
1	0.0834	0.0520	0.530	44.43	1.974	3.108	316.8
¾	0.0875	0.0551	0.552	42.15	1.872	3.048	310.7
½	0.0923	0.0587	0.573	39.82	1.765	2.985	304.3

On the basis of experimental results, α is considered equal to 0.75.

SYSTEM STUDY AND ENGINE SIZING

The comparison between an advanced LRE and a CDWRE has been done[6][7], 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 H_2-O_2 mixture. Such a short combustion chamber length will be helpful to reduce the wetted area of the engine because an 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 CDWRE will have a slightly better 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.

This difference between the CDWRE and the LRE decreases as the operating pressure inside the engine and the nozzle expansion ratio increases, but the CDWRE system presents the advantage that the considered performances are obtained with largely lower feeding pressure (here 2.2 MPa instead 7.0 MPa) (Table 2).

Table 2. Specific impulse and thrust of a CDWE and a LRE (*) operating at the same maximum pressure, with different nozzle expansion ratio.

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

Moreover, the integration of a CDWRE can be very attractive when considering an aerospike configuration as it is shown by Figure 4.
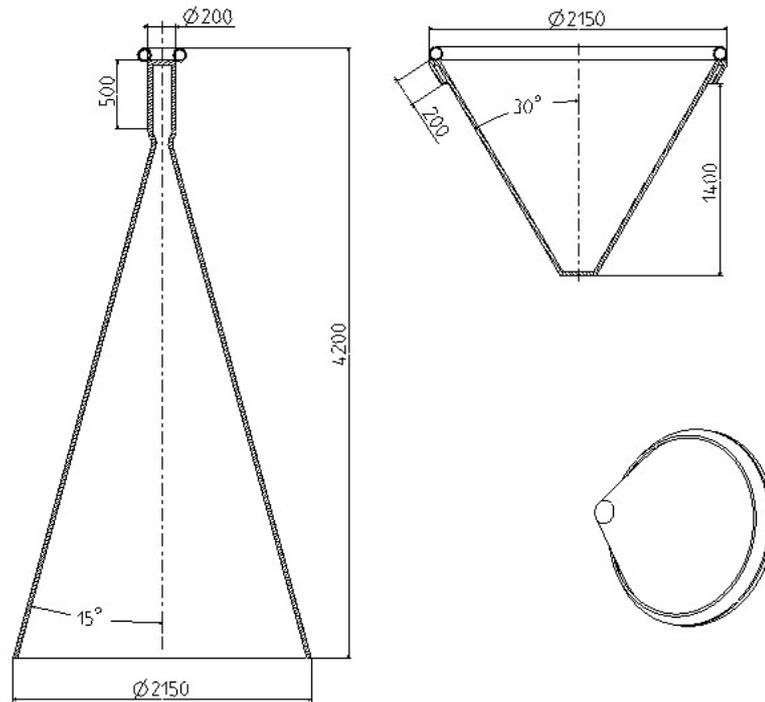

Figure 4. Comparison between equivalent classical LRE and CDWRE

EXPERIMENTAL EVALUATION OF KEY TECHNOLOGY POINTS

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.

Thrust vectoring investigations

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 simpler 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, 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 show 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 (Figure 5).
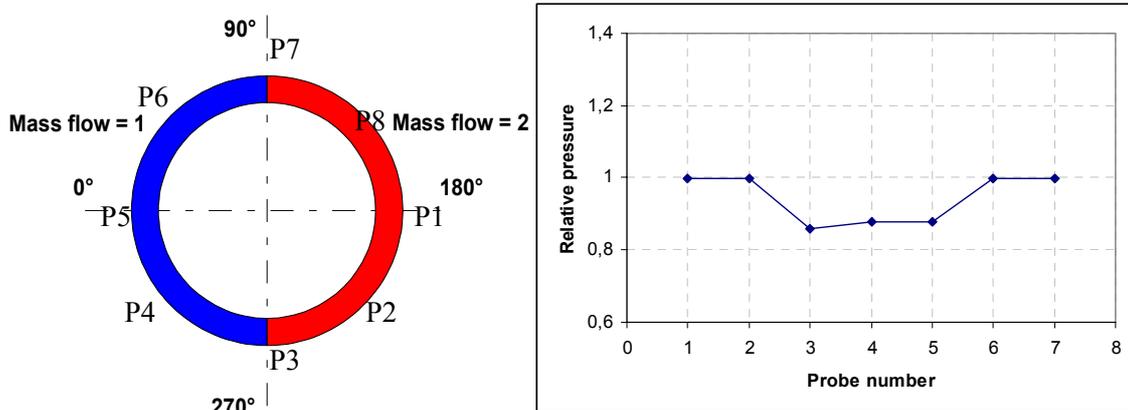

**Figure 5. Example of thrust wall relative pressure from
probes P1 to P7 (P1 is the reference value)**

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.

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 (Figure 6).
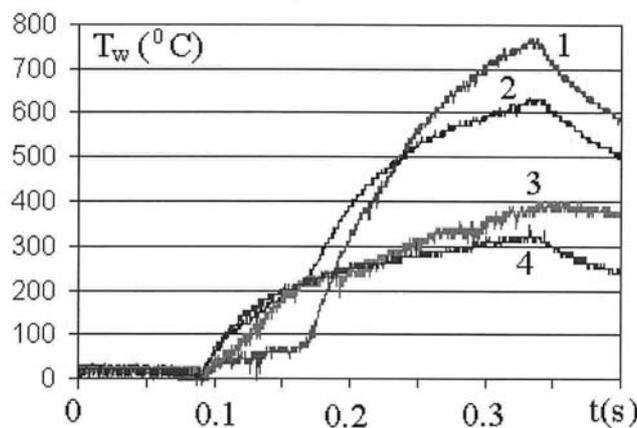

Figure 6. Typical wall temperature along the combustion chamber with H_2+O_2 mixture (1-8 mm from thrust wall ; 2-20 mm ; 3-50 mm ; 4-90 mm).

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 15 $MW.m^{-2}$ with local values even higher.

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[8]. 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.

Composite materials could achieve higher wall temperature (up to 1800 K) even in oxidative 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. Recently, these two parts successfully sustained a series of short duration (0.5 s) tests without apparent damage to the material surface (Figure 7). Detailed analysis of these parts is still in progress and new test series with harder conditions could be performed in near term.

Figure 7. Composite parts before (left) and after the first test (right).

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 CDWRE 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 (Figure 8), 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.
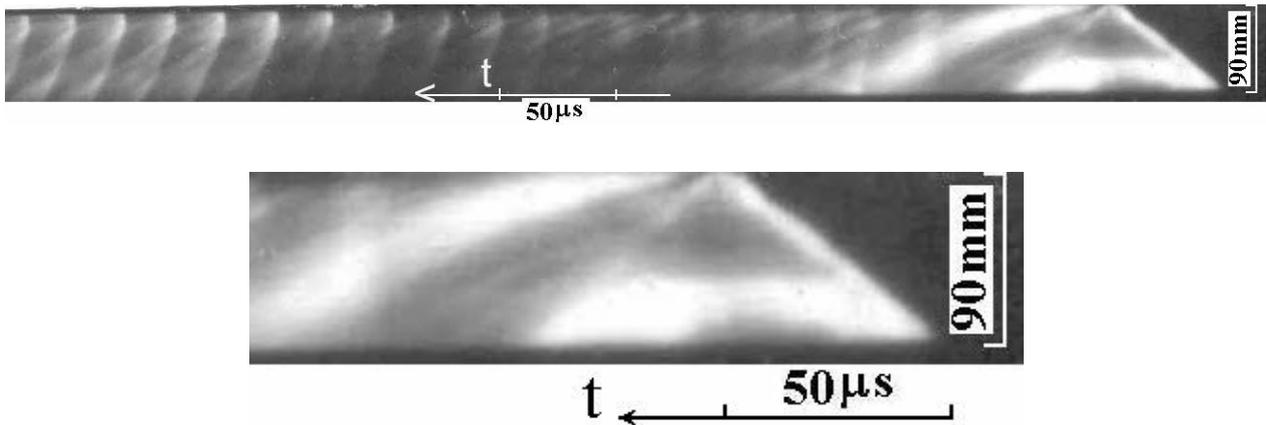
Figure 8. Fragment of the photographic record with rotating detonation initiation.

In the case of a positive TDW initiation, the static pressure inside the combustor increases to a much higher level (between $0.8\ 10^5$ Pa and $1.25\ 10^5$ Pa) than when no detonation occurs (due to the lack of a geometric throat at the exit of the combustion chamber).

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) (Figure 9).
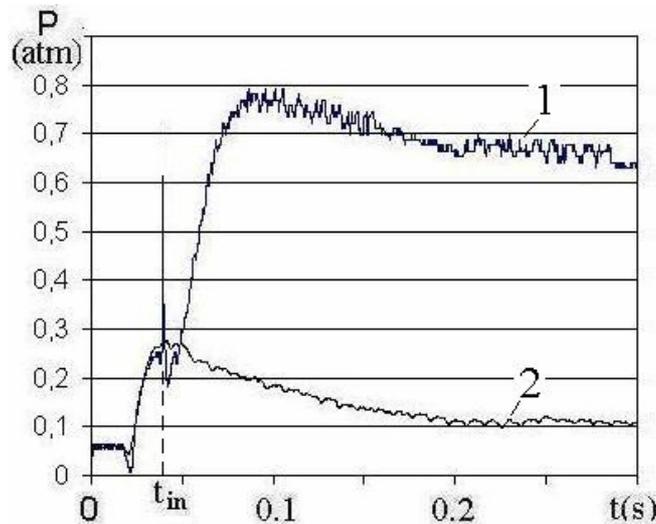

**Figure 9. Static pressure history with detonation initiation (1)
and without detonation initiation (2).**

NUMERICAL SIMULATIONS

Some preliminary simulations were performed using FLUCEPA code and a 9 step kinetic model for H_2 and O_2 combustion and considering a single detonation wave with forced ignition.

It was found that this code was sufficiently robust to deal with the large pressure and velocity gradients found in a detonation front without the need to use mesh adaptation (Figure 10).
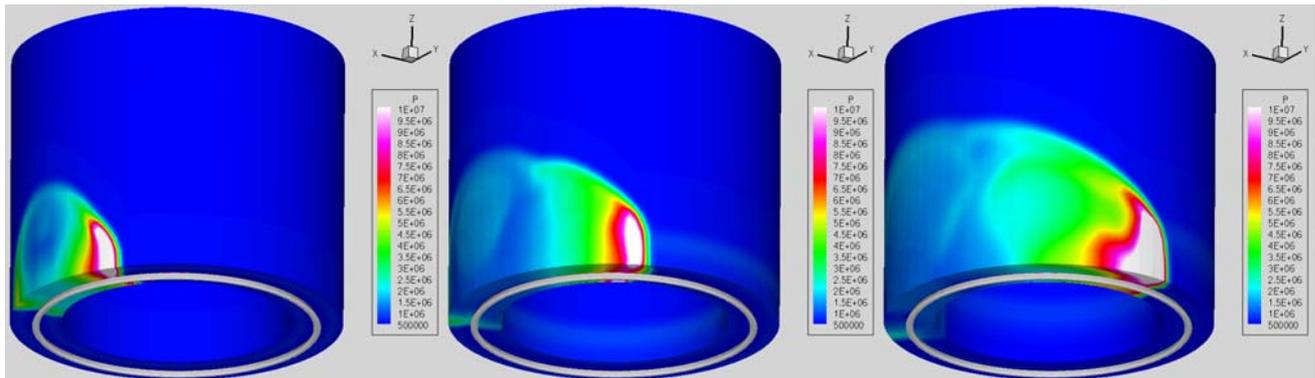
**Figure 10 - Detonation propagation in an annular chamber 10 ms, 20 ms and 30 ms after ignition
(H_2+O_2 stoichiometric mixture in a 100 mm diameter chamber).**

This robustness is a critical point because in the case of cylindrical detonation propagation, the pressure and velocity slopes before and after the shock wave are infinite, so in this case the detonation wave is a true double discontinuity, a real difference between CDWE and PDE internal flow simulations.

The steadiness of the Transverse Detonation Wave propagation is also very sensitive to the injection conditions while the existence of consecutive detonation waves radically changes the flow structure.

In order to better represent the actual flow field, further works have been performed by the French ICARE Research Lab. 2D Euler simulation has been used with a H2/O2 chemistry model using 6 species and 7 reactions. On the basis of experimental results, the width of the computation grid is determined as the distance between two consecutive detonation waves. Then a periodical condition is imposed: conditions on the right end of the grid being imposed to the left end. Figure 11 gives the circumferential U and axial V speed components. One can note that the exhausting flow is mainly oriented to the chamber axis with limited remaining U speed compared to the large V speed.
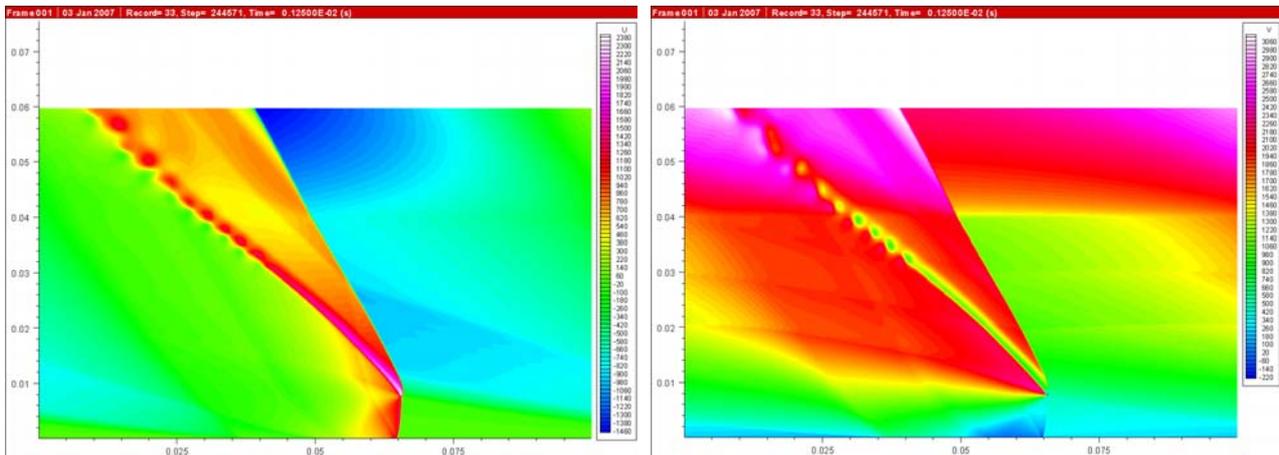

Figure 11. Circumferential U and axial V speed components

Computation results exhibit a neutral line of Mach number at approximately 40% of the distance between two consecutive detonation waves (Figure 12).
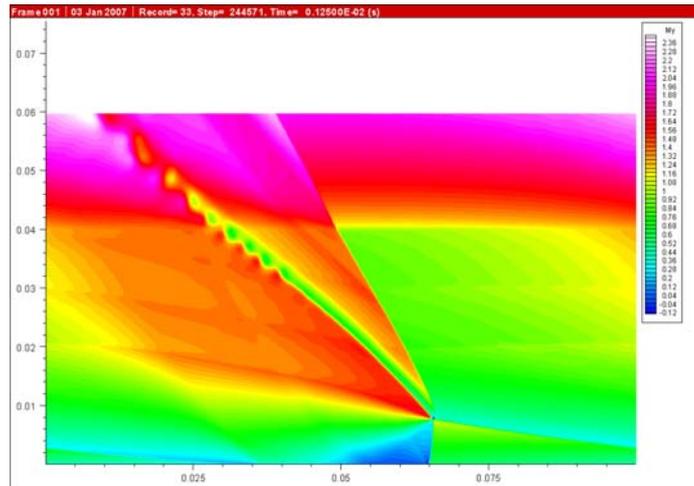
Figure 12. Axial Mach number field

DEMONSTRATION ENGINE

Based on previous studies and the growing potential of such concept, a demonstration engine has been designed. This actual-size engine (Figure 13) 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 with the change of supply lines and injection wall. This engine mock-up is modular and actively cooled.

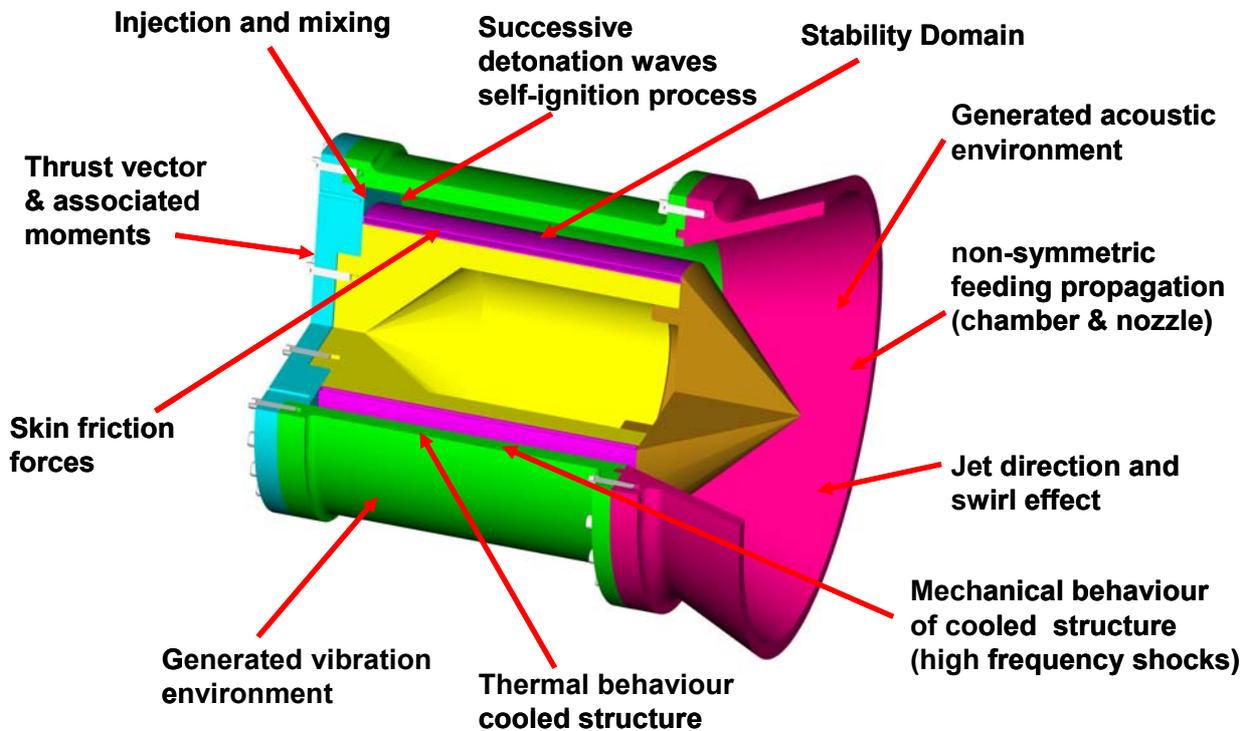**Figure 13 - cutout of the demonstration engine**

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.

Thanks to its modularity, the engine will be used, in a first step, as a non-flying workhorse which will allow addressing 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 non-symmetric 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.

CONCLUSION

Since a few years, MBDA France 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 tested within the next years.

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