New Combustion Concepts to Enhance the Thermodynamic Efficiency of Propulsion Engines

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The reduction of fuel consumption in future propulsive engines is an ambitious target that will be reached only with a technological breakthrough. Two of the possible solutions are being investigated experimentally and numerically by MBDA France, ONERA, PPRIME and SAFRAN Tech. Changing the actual thermodynamical cycle through the use of Constant-Volume Combustion or Rotative Detonation concepts could theoretically enable this target to be reached. Implementing such concepts requires a deep knowledge and control of several basic phenomena that will occur and interact in real engines, such as: mixing processes, ignition, flow effects, dilution by residual burnt gas, etc.

This article presents recent studies carried out on these elementary processes that must be considered in high-velocity flows and under non-stationary conditions, whatever the concept (CVC or RDE). The results provide a comprehensive insight into constant-volume combustion and detonation dynamics from simulation and experiments on a reduced scale or full scale prototype, which enables the physical phenomena to be understood and modeled, and the potential of such concepts for future propulsion to be highlighted.

Introduction

The Advisory Council for Aviation Research and Innovation in Europe (ACARE) set the goals to reduce CO_2 emissions by 75% and NOx emissions by 90% in 2050 relative to the aircraft emissions produced in 2000. After sixty years of constant research and development efforts, aircraft engines have now reached a high level of maturity. For example, the ability to use high operating pressure (OPR) and by-pass ratios (BPR) led to CO_2 emissions being reduced by 60%. However, there is also broad consensus among experts that these engine technologies have been stretched to their limits, leaving limited potential for further significant improvement in their performance. Thus, only technological breakthroughs will enable the aviation industry to reach the 2050 ACARE goals.

With regard to the combustion process, which is the one that generates most of the entropy for current engines, two alternatives to the usual Joule-Brayton cycle must be considered because they could lead to a remarkable reduction of around 20% [1] in the specific fuel consumption:

1) The constant-volume combustion process (CVC), which for jet engines is described by the Humphrey thermodynamic cycle. The potential of this cycle has been known for a long time and its analogue for piston engines has been successfully used.
2) The combustion detonation mode is described by a so-called "detonation cycle" proposed by Fickett and Jacobs (FJ).

The CVC-Humphrey and Detonation-FJ cycles applied to an airbreathing engine are very similar and lead to attractive improvements of the engine thermal efficiency. In addition, because a large part of the pressure increase is provided by the combustion process, the high pressure compressor could be eventually removed, opening the way to lighter and more compact engines.

Today, no turbine engine operates with the CVC mode, so there is no information available on kerosene CVC properties. Moreover, the thermodynamic conditions, flow characteristics, turbulence, dilution by residual burnt gases, and space and time scales for CVC turbine engines will be very different from those of piston engines, and prevent researchers from using most of the literature related to combustion in piston engines. Similarly, applications of detonation to propulsion have only been considered for a short time, although its fundamental processes have been studied for more than a century, essentially in the domains of defense and safety.

Thus, as regards airbreathing engines, estimates from ideal cycles indicate that the CVC and the Detonation modes would provide significantly higher efficiencies than constant-pressure combustion (CPC) because they both induce higher pressure and temperature in the burnt gas. In a detonation, this compression is obtained before the combustion zone, by means of the detonation leading shock that induces the chemical reaction process. In contrast, in a CVC engine, the pressure increase is achieved at the end of the heat release induced by the combustion itself. These two combustion modes, namely CVC and detonation, raise key scientific issues that require research efforts before they are applied for propulsion: some of them are currently being investigated within the framework of the Chair CAPA [2] dedicated to “Alternative Combustion Modes for Airbreathing Propulsion” and financially supported by ANR, SAFRAN Tech and MBDA.

The detonation cycle can also be used for liquid rocket propulsion, offering the possibility of improving engine performance, as well as some benefits for the propulsion system [26]. This can be an important breakthrough for space launcher technologies, because the performance of todays’ liquid rocket engines is very close to the theoretical limit corresponding to the CPC cycle.

Constant-Volume Combustion mode for propulsion

The CVC mode is aimed at (i) benefiting from the better thermodynamic efficiency of isochoric combustion (Humphrey cycle), compared to isobaric combustion (Brayton cycle), and at (ii) reaching higher OPR, compared to conventional turbine engines. Depending on the engine configuration, the isochoric combustor could replace either the combustion chamber, or both the high-pressure compressor and the chamber. Preliminary estimates indicate that the expected benefit in fuel specific consumption could reach a few tens % [3]. This gain would be even higher for small engines, where size limitation does not allow the same compression ratio as in conventional turbine engines.

A few technological concepts have been considered, to allow for continuity in the quasi-steady flow between the turbine engine and the constant-volume combustor. For hypersonic flight up to Mach 4, DARPA (USA) is supporting research on CVC through the Vulcan Program (33 million US dollars), whose results will be also used for turbine-engines and ground-based engines (Vulcan II). Other concepts are currently being investigated, such as the “Wave Rotor” (USA, Glenn Research Center, NASA), “Shockless Explosion Combustion” (Germany, Berlin TU CRC 1029 [4]), the Rim-Rotor-Rotary Ramjet (Canada, Sherbrooke University, [5], [6]) and the “*Thermoréacteur*” (France, DGA, consortium COMAT/Turbomeca/PPRIME, 2011-2014). The Wave Rotor features a rotating barrel of tube combustors, the inlets and outlets of which are enclosed by two walls with windows for fresh-gas intake and burned-gas exhaust. The barrel rotates at a given speed, depending on the intake, combustion and exhaust duration, but independently from the rotation of the low- or high-pressure shaft [7]-[8]. The *Thermoréacteur* concept (Patent FR2945316, 2009) features rotating valves inside a fixed combustor, allowing for intake and exhaust. The consistency of the CVC concept has been proved with successful experiments and simulation [3], and some scientific key issues have arisen.

Integration of a CVC chamber into an engine

The theoretical gains provided by CVC are extremely attractive. However, since the CVC system (including the compressor and turbine) will work in a completely different manner compared to conventional systems, complications arise in the integration of such technology into a turbo-engine. The side effects (cooling processes or compressor and turbine efficiency) may strongly affect the overall performance of the machine and completely cancel out the benefit of CVC. Indeed, the combustion system will periodically admit fresh air and periodically release burnt gases at high pressure and temperature. Therefore all of the surrounding components will undergo the unsteadiness generated by the combustion device. A CVC system will comprise multiple combustion chambers, which will be operated with a phase shift in order to smooth the average flow rate and minimize the overall pressure and temperature fluctuations. Nevertheless, temporal and spatial variations will remain significant, especially at the turbine entrance.

In conventional turbo engines, the compressor upstream delivers a steady flow with a quasi-uniform pressure distribution to the combustion system. The stability, efficiency and flow characteristics of steady flow compressors are well known. Designing a compressor operating under imposed rotating distortion and unsteady throttling without any loss of efficiency and stability is a real challenge that must be embraced in order to make CVC possible. The same analysis applies to the turbine, which will be fed with burnt gases at high pressure and temperature at the beginning of the exhaust phase and with the compressor pressure gases at almost the temperature of the fresh air (in the worst case) at the end of the scavenging phase. As a result, the flow velocity within the turbine stages will vary a lot during a cycle, whereas the velocity of the rotor blades will remain unchanged because of the significant mechanical inertia of the compressor-turbine spool. Therefore, the incidence on the blades will vary a lot, which can generate a dramatic loss of efficiency. A turbine operating under such conditions must be carefully studied and designed, in order to preserve the full advantage of the CVC.

In addition to this specific aerodynamic behavior encountered in turbomachinery working with a CVC system, many others aspects must be carefully studied as well. For instance, the vibrations induced by the pulsating overpressures must be mastered to provide a lifetime equivalent to conventional engines. The cooling and vent systems need to be completely rethought, since the maximum pressure point is in the hot gases and no longer in the fresh gases. Integration of such a technology is as challenging as the technology itself. Up to now, knowledge of the physical phenomena involved in combustion, compression and expansion processes does not allow the gain of such a real system to be quantified. As the center of the engine concept, combustion has to be studied first.

Laboratory scale CVC chamber experimentation

During the *Thermoréacteur* [3] project, experimental work has been carried out to address combustion and ignition issues related to the CVC concept. The facility set up in PPRIME is an original combustor designed by COMAT, operating the successive phases of a CVC cycle (intake, combustion, exhaust) using rotary valves. The 0.65 L combustion chamber is downstream from a carburation chamber, followed by an outlet duct to the atmosphere (see Figure 1). The firing operation is achieved with the injection of 240 mg of

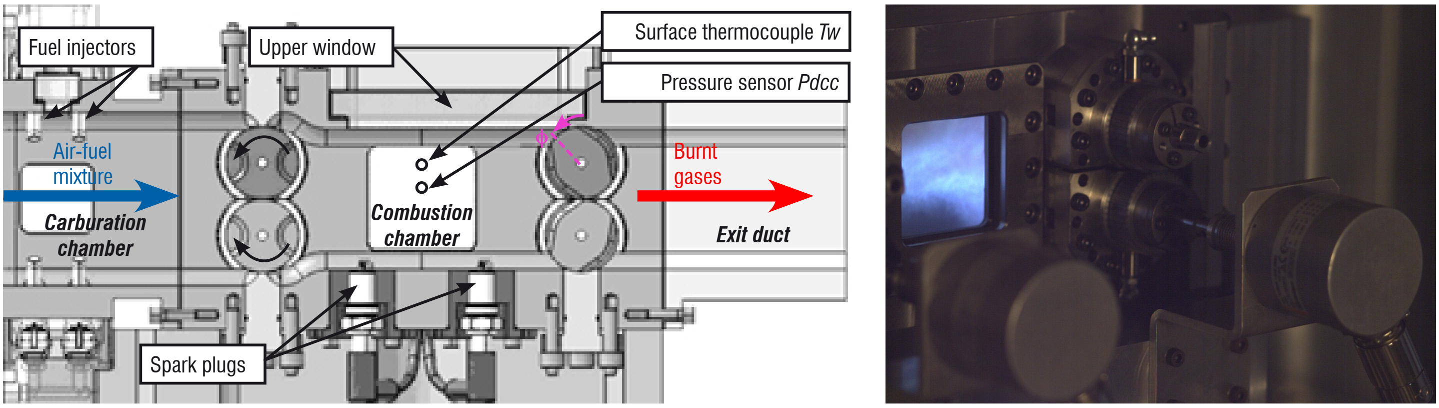


Figure 1 - Schematic diagram of the combustor and firing operation

isooctane into air at 0.3 MPa and 120°C, with a frequency of 40 Hz, $\Phi = 36°$ (phase difference between rotary valves), and ignition at intake valve closure ($\theta^* = 125°$). Flame propagation is resolved by high-speed imaging (Phantom v310, 3 kHz, 12 bit). Velocity measurements are performed using a PIV system (LaVision High-SpeedStar, 2.5 kHz).

After spark ignition, the flame propagates quickly with a stretched flame front, thus indicating a highly turbulent flow inside the chamber (see Figure 2). The flame is mainly blue, which is characteristic of a lean premixed combustion. Yellow zones appear, due to the combustion of remaining fuel droplets that have not yet completely vaporized. Overall, combustion propagates in a stratified field of velocity and composition, leading to the consumption of the charge mostly during the constant-volume phase.

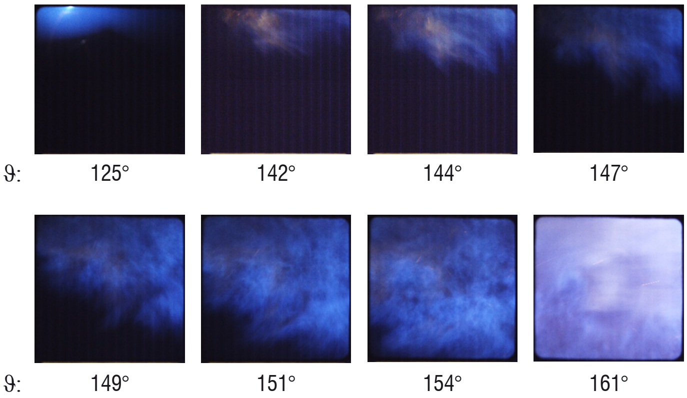


Figure 2 - Flame propagation – Ignition point C, 30 mJ, $\vartheta^* = 125°$

This operating point is also characterized by the combustion pressure (piezoelectric sensor Kistler 6125C) and wall heat flux Qw (surface E-thermocouple): see Figure 3. Average results confirm that the pressure increase due to combustion occurs mostly during the constant-volume phase, while the wall heat flux increases simultaneously due to flame-wall interaction and burnt gas convection.

The control of the air-fuel mixing is complex in this facility, because fuel injection is performed inside the carburation chamber, resulting in a “port-fuel injection” chamber. Unlike direct fuel injection, this strategy does not allow real control of the fresh charge composition before combustion. Indeed, the intake process begins with a scavenging phase, so most of the air-fuel charge is exhausted. The air-fuel mixture generated in the carburation chamber has an overall equivalence ratio of 1.18, which is measured through data processing. The fresh charge remaining inside the combustion chamber at the end of the intake is composed of air-fuel mixture, as well as residual burnt gas from the previous cycle. Therefore, the overall equivalence ratio inside the combustion chamber before ignition cannot be controlled precisely during operation, but the numerical simulation of this experiment reveals that the residual burnt gas represents up to 20% of the fresh charge [31] and varies from cycle-to-cycle. However, evaluating the local or global equivalence ratio remains a challenge due to flow unsteadiness and to the vaporization of fuel droplets, which can be incomplete, resulting in fuel deposit at the wall.

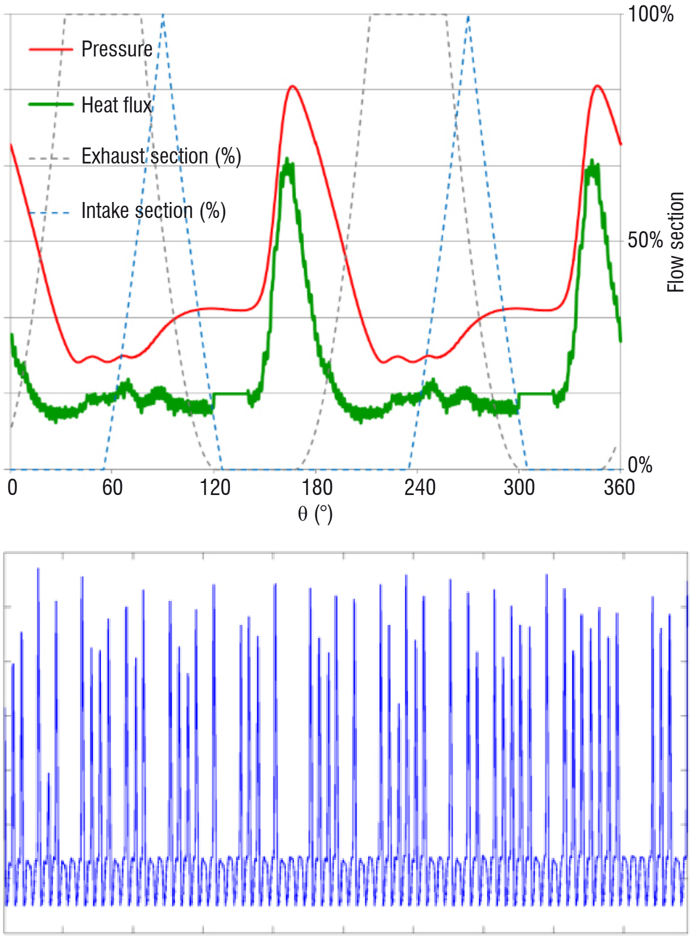


Figure 3 - Experimental signals in average (top) and successive pressure cycles (bottom) – Ignition point C, 30 mJ, $\vartheta^* = 125°$

Effect of experimental conditions on the successful operation of a CVC chamber

The efficiency of a CVC chamber requires the successful ignition of each cycle. However, experimental results demonstrate that misfires can occur, depending on ignition conditions (see Figure 3). Moreover, the pressure peaks obtained experimentally are lower than expected from ideal adiabatic isochoric combustion: this may be partially due to the wall heat loss (which is measured at a single point) but mostly due to the clearance between rotary valves, which allows the flow to exit as pressure increases during combustion. This point deserves further analysis in order to determine which phenomenon is prominent, using unsteady flow modeling for instance.

To reduce misfiring, the main solutions identified so far are to change the position of the ignition point, the ignition phasing, and the energy of the ignition discharge:

Ignition conditions	Ignition probability	Velocity V	Combustion time $t_{10\text{-}90}$ (a.u.)
$\theta^* = 125^\circ$, point C, spark 30 mJ	65.4 %	14.7 ± 1.13 m/s	96 ±12%
$\theta^* = 135^\circ$, point C, spark 30 mJ	100 %	11.8 ± 1.20 m/s	100 ±10%
$\theta^* = 125^\circ$, Point F, spark 30 mJ	48.3 %	17.2 ± 1.44 m/s	85 ±18%
$\theta^* = 125^\circ$, Point C, spark + arc 300 mJ	100 %	14.7 ± 1.13 m/s	94 ±14%

Table 1 - Effect of spark conditions on ignition success and combustion pressure

At first, ignition was located at point C, on inlet valve closure ($\theta^* = 125^\circ$) or later ($\theta^* = 135^\circ$), based on PIV measurements of the velocity field (see Figure 4). This additional delay allows the local flow velocity to reach a lower value, and thus suppress misfiring (see Table 1).

In order to confirm the effect of gas dynamics, the ignition point was moved from the upstream corner (point C) toward the center of the chamber (point F). Point C exhibits a higher ignition probability, thanks to a lower average flow velocity. However, when ignition succeeds at point F, the higher flow velocity leads to a substantial gain in combustion time (see Table 1). The influence of both ignition phasing and location indicates the effect of gas dynamics over the ignition and combustion processes. This shows the possible role of kernel blow-off or flame stretch due to high velocity magnitude.

Another solution to overcome misfires is to increase the spark discharge energy (30 mJ) by allowing an arc phase of higher energy (300 mJ). This result shows the effect of the discharge energy on ignition success: increasing energy prevents misfires, even at high velocity (see Table 1).

Far-seeing research imposed by CVC concept

Whatever the final concept retained to operate a Constant Volume Combustion engine (not necessarily the *Thermoreacteur*), the elementary phases encountered during the cycle (intake, mixture preparation, ignition, combustion and exhaust) recall those of the piston engine cycle, but the absence of piston motion leads to substantial differences. Therefore, the literature concerning internal flows, ignition and combustion in piston engines is very extensive, but not wholly consistent with the present cycle. The key issues indicated hereafter deserve specific investigation:

i) The intake phase involves mostly internal aerodynamics, creating a specific spectrum of flow structures from large-scale motion to turbulence.

ii) The preparation of a fresh mixture, diluted by residual burnt gases, depends on the fuel injection, the flow and temperature fields of the media influenced by molecular mixing, and the turbulent and bulk scale high-speed sheared flows that take place in such chambers.

iii) The ignition phase is a key point of pulsed combustion. Indeed, the use of fuel-lean mixtures that reduce fuel consumption and emissions, or the high flow velocity, increase the risk of misfire.

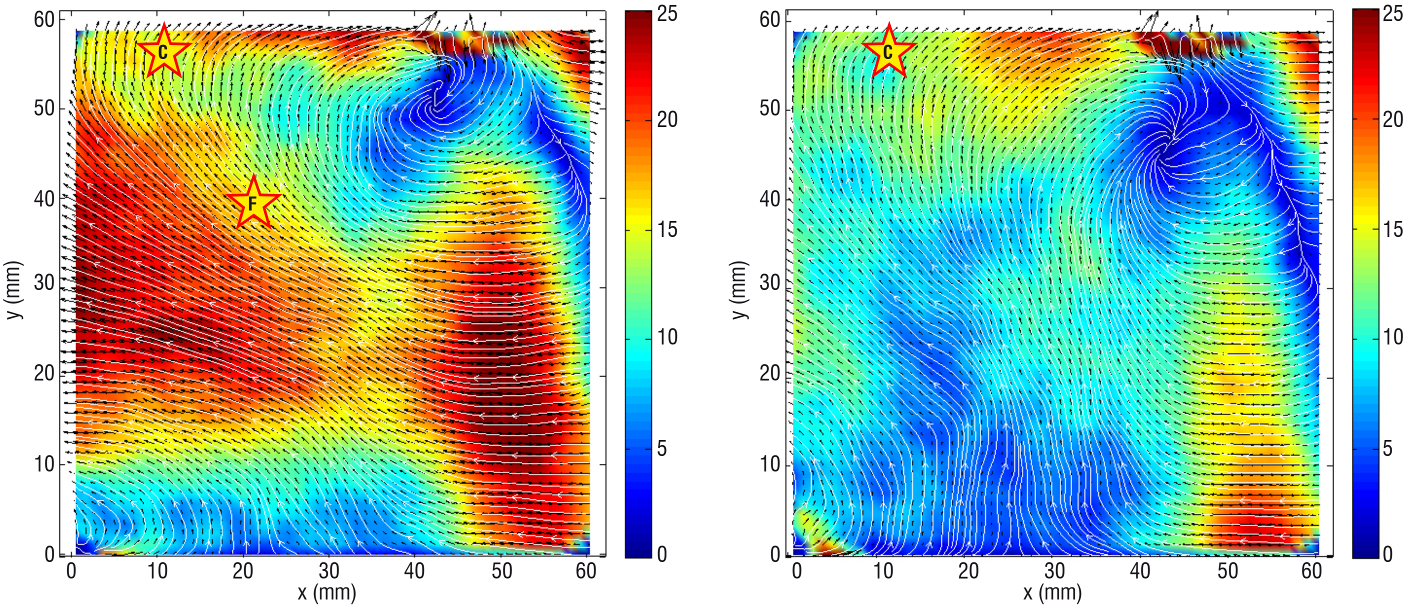


Figure 4 - Average velocity field at $\theta^* = 125^\circ$ (left) and $\theta^* = 135^\circ$ (right)

Thus, it is necessary to characterize the ignition conditions for jet fuels. Real thermal energy transfer to gas must be mastered and the minimum ignition energy and flammability limits of kerosene-air-diluent mixtures must be investigated. Since current aeronautic igniters are only used to start the engine, the technology used does not require a very large number of sparks to be performed like in a piston engine. Due to the pulsed combustion process implied by CVC mode, new ignition technologies should be developed to increase the lifetime of the igniter, to perform many more sparks.

iv) Finally the associated combustion regime cannot be estimated *a priori* (flamelet regime, wrinkled flamelets, thickened flames, auto-ignition, etc.) without strong control of all of the previous phenomena.

These scientific key issues, especially iii) and iv), are investigated within the framework of the CAPA Chair.

Detonation Combustion Mode for propulsion

Continuous wave detonation engine

Detonation is a combustion regime that provides an extremely rapid release of thermal energy. It is a supersonic combustion wave that generates great overpressures, about 15 to 40 times the initial pressure in gaseous reactive mixtures, and very high temperatures, up to 4000 K depending on the considered fuel and oxidizer. Thus, as regards its application to propulsion, implementing the detonation mode to replace the isobaric combustion mode in most propulsion engines represents a technological breakthrough for increasing the propulsive efficiency.

The main three detonation-based propulsive concepts that have been considered so far are the Oblique Detonation Wave Engine (ODWE), such as the RAMAC, the Pulsed Detonation Engine (PDE) and the Rotating Detonation Engine (RDE).

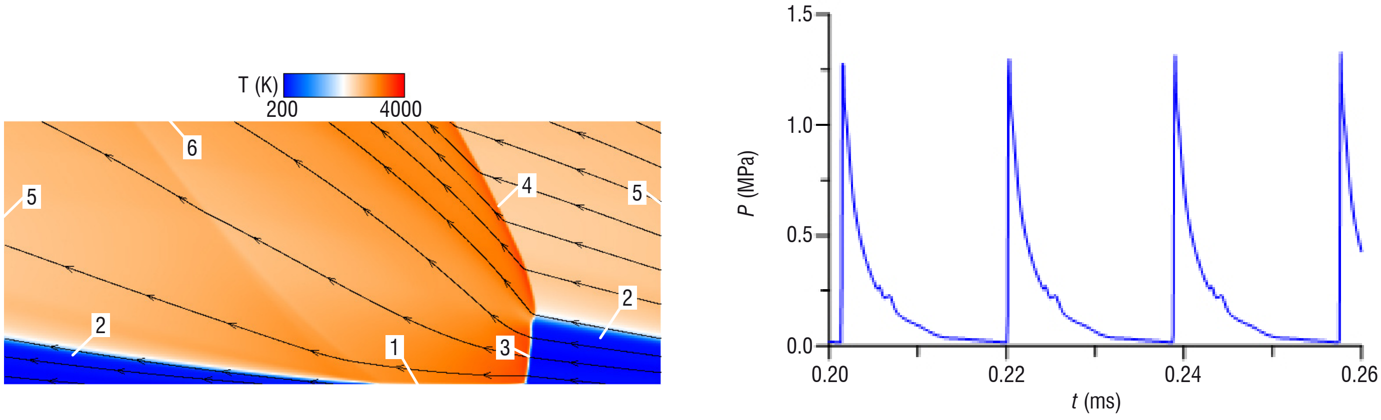
RDE has several important advantages over PDE: i) no complex valving or moving parts; ii) no need for repetitive detonation initiation; iii) a two-order of magnitude higher frequency (~10 kHz for RDE, ~100 Hz for PDE), hence much less noise and vibration; iv) much more uniform flow at the combustion chamber exit, without strong pressure and velocity fluctuations; v) easier integration into the propulsion system, due to the aforementioned factors and also thanks to the annular shape (unlike the tubular PDE).

The first studies on continuous detonation in an annular space date back to the 1960s. In particular, continuous detonation was the subject of many experimental and numerical studies (Zhdan *et al* 1990 [12]) conducted at the Lavrentyev Institute for Hydrodynamics (LIH, Novosibirsk). Various annular chamber geometries were considered to study the stabilization of a regime of rotating transverse detonation waves for several reactive mixtures with different sensitivity to detonation.

Recent studies on propulsion by detonation show an increasing interest in the RDE option in many countries, mainly France (Canteins 2006 [9]), Falempin *et al* 2006 [13], Falempin *et al* 2011 [14], Davidenko *et al* 2011 [15]), Japan (Hishida *et al* 2009 [16]), Uemura *et al* 2013 [17]), Poland (Kindracki *et al* 2011 [18]), China (Wang 2012 [19]), USA (Schwer and Kailasanath 2013 [20], Braun 2012 [21]), South Korea (Yi *et al* 2011 [22]), Russia (Frolov *et al* 2011 [23], Bykovskii *et al* 2009 [24]).

The operation of a RDE engine can be illustrated by considering the results of a 2D simulation with the CEDRE code (ONERA) shown in Figure 5 [30]. This simulation represents an idealized case with the following assumptions: the injection of H_2 and O_2 as gaseous propellants is fully premixed and uniformly distributed over the injection plane; the wall effects (annulus curvature, skin friction, and heat exchange), as well as the viscous effects in the flow are ignored. Nevertheless, it can be taken as a reference for more realistic simulations accounting for the aforementioned factors. This case has the following main characteristics: the domain dimensions are 50 mm by 20 mm; the injected mixture has a stoichiometric composition at a total temperature of 300 K; the mass flow rate per unit section is 100 kg/(s m^2).

The main flow features are visible in the temperature field in Figure 5a. The injection creates a layer of fresh mixture corresponding to the low-temperature zone, in which a detonation wave propagates from left to right. The injection is blocked right behind the detonation front



a) b)

Figure 5 - 2D simulation of a rotating detonation with distributed injection of a H_2-O_2 mixture.
a) Instantaneous temperature field with superimposed streamlines in the detonation reference frame:
1 – injection plane, 2 – fresh mixture layer, 3 – detonation front, 4 – shock front, 5 – periodic boundaries, 6 – outflow plane.
b) Pressure record at a fixed point on the injection plane; the spikes correspond to detonation passages.

by the compressed burnt gases, but the mixture is re-injected at some distance from the detonation during gas expansion. The burnt gas expansion is indicated by the streamline divergence past the detonation front, as well as by the pressure signal evolution in Figure 5b. This expansion also results in an oblique shock wave in the hot gases, which moves together with the detonation. The detonation wave propagates at a constant speed of 2670 m/s. The temporal period between detonation passages, defined by the geometric period, is less than 19 μs, which corresponds to a frequency of about 53 kHz.

Scientific key issues

The most difficult points to understand and to master are the basic physics of the propagation of the self-sustained rotating detonation in a narrow channel with the selection mechanism of the wave number and of the direction of the wave propagation. All of these dynamical features are directly related to the non-idealities present in the combustor, such as:

i) the curvature of the chamber and the width of the channel.

ii) the non-homogeneities of the initial mixture, induced by the mixing of fresh reactants in the chamber and by the mixing of fresh and burnt gases between successive detonation fronts.

These non-idealities combine in such a way that each wave front is very different from that described by the ideal Chapman-Jouguet model and that the initial mixture is strongly heterogeneous and unequally distributed in the annular chamber.

Non-ideality effects on detonation front propagation

Non-ideal propagation of detonation refers to dynamical phenomena that make detonation behaviors and properties different from those of the ideal detonation defined by the Chapman-Jouguet (CJ) model as a fully-reactive, planar and self-sustaining discontinuity wave. Detonation behaviors are often non-ideal, meaning that at least one of these three conditions is not met. The CJ detonation should thus be considered as the limiting process useful for defining reference thermodynamic states and indicating how far from ideality real detonations can be. Depending on whether the detonation regime is to be used or avoided, the fundamental problems are to determine sufficient conditions to obtain a quasi-CJ regime, and those that prevent detonation from propagating non-ideally.

In the context of using detonation as a combustion process for propulsive devices, the studies should thus address two objectives. The first is to determine the minimum size and the optimum shape of the combustion chamber, so detonation propagates as a quasi-CJ wave. The second is to develop robust low-energy ignition devices capable of generating detonation within characteristic times and lengths much shorter than those of the detonation propagation in the chamber. These objectives should be met for large ranges of mass flow rates and initial pressures.

Non-ideal detonation dynamical phenomena can be categorized into two groups. The first gathers global behaviors induced by initial and boundary or geometric conditions that lead to an incomplete combustion process in the detonation reaction zone. They result essentially from the adiabatic losses due to divergence of the reactive flow. Their most visible effect is a curved detonation leading shock, at the scale of the reaction zone thickness. The main consequence is the existence of critical sizes for detonation, such as minimum radii for diverging spherical detonations, minimum thicknesses for semi-confined detonations, etc. Indeed, adiabatic losses compete with heat production in the reaction zone, and too large losses lead to detonation quenching. The second group refers to local behaviors induced by the intrinsic instability of the reaction zone, which cause the reactive flow to have a specific three-dimensional cellular structure. This cellular instability results from the high sensitivity of the chemical reaction rates to very small state fluctuations, essentially that of temperature. The main consequence is that, close to the propagation limits, detonation has strongly unsteady and three-dimensional behaviors. Global and local dynamical behaviors often combine, and analyzing detonation dynamics can be a difficult task.

The simplest relevant picture of detonation is a shock followed by a high-pressure, high-temperature zone of chemical reactions triggered by this shock (Crussard, Zel'dovich, Von Neuman, Döring, ZND). Long enough after ignition, detonation reaches a self-sustaining propagation regime, such that the dependency domain of the leading shock is limited to all or part of the reaction zone. The whole flow behind the shock expands and two domains should be distinguished. The closest to the shock consists of most of the reaction zone and sustains this shock. The other is essentially made up of burnt products and does not sustain the shock. The separation boundary propagates with the local velocity of the acoustic perturbations (the "sonic surface").

Self-sustaining regimes result from a balance between the production of chemical energy, triggered by the leading shock, and the losses induced by the adiabatic expansion of the reactive flow behind the shock. Balance exists only if the sonic head of the release wave is far enough away from the shock for energy production to be high enough to counteract adiabatic cooling. For the planar self-sustaining detonation, the sonic head of the release wave is located at the end of the reaction zone (except for "pathological" reactive mixtures), because all of the chemical energy is produced between the shock and the release-wave head. This is the Chapman-Jouguet (CJ) detonation, which thus propagates with the maximum velocity D_{CJ}. For curved self-sustaining detonations, the sonic head of the expansion wave is located slightly before the end of the reaction zone. Such quasi-CJ detonations thus propagate with velocities smaller than D_{CJ}, since a small part of the available chemical energy is lost out of the shock dependency domain. Too large expansions cause too much energy to be lost, balance between energy production and adiabatic losses cannot be achieved, and too strongly curved detonations cannot be self-sustaining. This explains the global dynamical behaviors of detonation.

The CJ model gives the ideal detonation velocity D_{CJ} and the properties (p_{CJ}, T_{CJ}, etc.) at the reaction-zone end of the self-sustaining, planar detonation. The Taylor-Zel'dovich (TZ) model describes the expanding unsteady flow beyond this reaction zone. The ZND model complements the CJ model with a one-dimensional steady description of the flow in the reaction zone. These 3 models are the minimum necessary set of calculations for determining relevant detonation properties and characteristic chemical lengths and times. However, neither of the CJ, TZ and ZND models can provide information on conditions for detonation propagation or existence, which can only be assessed by considering non-idealities. Estimating detonation properties and efficiency by means of the CJ and TZ models is physically relevant only if the ZND characteristic lengths and times are much shorter than those of the non-idealities.

The CJ properties are obtained from thermochemical calculations, they only depend on the composition of the combustion products at chemical equilibrium (the "energetic content"), and on the initial pressure and temperature of the considered mixture. The ZND reaction profiles and evolutions are obtained by solving the one-dimensional steady balance laws coupled with a chemical kinetics scheme. The TZ flow beyond the reaction zone can also be simply obtained. In particular, the pressure that is applied on a rigid wall where a CJ detonation would have been ignited is about $p_{CJ}/3$.

However, chemical reaction rates in gases are very sensitive to small temperature fluctuations at the detonation leading shock, so the ZND reaction zone is unstable. Experiments show that gaseous detonation fronts have a complex three-dimensional unsteady structure made up of shock and combustion waves with transverse and longitudinal motions. A cut of the flow shows that the interaction points between longitudinal and transverse waves draw diamond-shaped patterns as detonation propagates. These patterns are called detonation cells and can be easily recorded experimentally by means of soot-covered steel foils inserted parallel to the main propagation direction of detonation, (the very large pressures at the interaction points erode the soot, e.g., Figures 6 and 7). Cells are more or less regular depending on the mixture, but an average width has been often considered for sake of analysis. Measured average widths λ have thus been observed to correlate with a ZND chemical characteristic length Lc and with the initial pressure p_0 of the mixture. Many experiments thus show that $\lambda = k\,Lc$ ($k \sim 15$-30) and that $\lambda = A\,p_0^{-n}$. Thus, the larger the detonation velocity or the higher the initial pressure, the smaller the characteristic chemical length and the smaller the detonation cell. Also, a large body of experimental results indicates that the capacity of a mixture to accept the detonation regime is defined by the average cell width λ compared to the transverse dimension of the detonation set-up. Robust experimental correlations bind the cell width λ to so-called dynamical parameters of detonation. These are the minimum energy for direct initiation of detonation, the minimum radius for the existence of self-sustaining diverging detonation, the minimum tube diameter for detonation transmission into a large volume and, to some extent, the deflagration-to-detonation transition length.

For example, a self-sustaining detonation in a channel can propagate close to the ideal CJ or ZND conditions only if the channel transverse dimension (e.g., the tube diameter) is at least about equal to 1/3 – 1/2 the average cell width for the considered initial pressure and temperature. If not, only so-called marginal modes of detonation propagation can be observed, or no detonation at all. Marginal detonations are very unstable, fully three-dimensional, with a limited number of transverse waves on the front surface. In contrast, a self-sustaining diverging spherical detonation propagates only if the local detonation radius is large enough compared to the detonation cell width, i.e., $Rc \sim 20$-$40\,\lambda$. A CJ detonation propagating in a finite-diameter tube can be transmitted to a larger volume only if the tube-diameter is about at least $10\,\lambda$. For more complicated geometries, scaling laws relating the characteristic lengths of the system to the cell width can be obtained. Determining the cell width λ as a function of the initial pressure and temperature of the mixture is therefore the fundamental prerequisite for sizing a device meant for using or avoiding detonation. The CJ and ZND models must be viewed as describing the average properties of multi-front cellular detonations, i.e., detonations that propagate under geometry or confinement conditions compatible with a sufficiently large number of cells on the front.

To date, the capacity of a mixture to accept the detonation regime in a given system (geometry, size, etc.) can be assessed only by means of experiments. The key point is that detonation dynamics is self-similar with respect to the cell mean width. A typical methodology is thus to carry out experiments in small-scale systems, with initial pressure and temperature compatible with the identification of the dynamics and the limiting conditions for detonation. Then, after the coefficients of the scaling laws $\lambda = k.Lc$ and $\lambda = Ap_0^{-n}$ are obtained, extrapolation can be used to anticipate detonation behaviors for larger systems or other initial pressures and temperatures.

Figure 6 shows supercritical and critical detonation transmission through a curved channel from a straight one with the same square section, and detonation quenching when the channel is too curved. Supercritical transmission (Figure 6, left) is the case of a channel curvature that does not influence detonation propagation. The soot foil shows that the cell mean width is practically the same in the straight and curved parts of the channel. Critical transmission (Figure 6, center) is the situation for which channel curvature influences detonation propagation, but not sufficiently to prevent detonation transmission. The soot foil indicates that the cell mean width increases very rapidly from the point on the inner face of the channel where bending begins and detonation starts undergoing lateral expansion. Detonation then keeps curving and decelerating, mean cell width increases, and successive detonation quenchings and re-initiations induced by transverse shock reflections at the channel faces can be observed. However, detonation survives all along the curved channel length. The sub-critical case (Figure 6, right) is the situation for which channel curvature is too strong, and detonation eventually quenches despite a few attempts of re-initiation in the form of marginal detonations. This is an example of interplay between global curvature effects induced by the system boundaries, and local dynamical behaviors, from a multi-cellular front to marginal propagation and quenching.

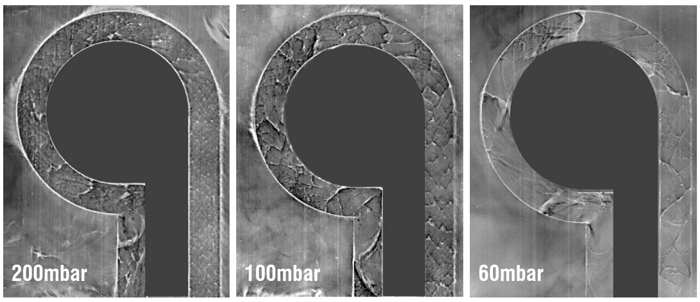


Figure 6 - Detonation dynamics in a curved channel.
Left: supercritical transmission. Center: critical transmission.
Right: quenching (Florian Gineste, 2015)

Figure 7 shows the dynamics of a detonation in a mixture with a non-uniform distribution of composition in a square-section channel. The gradient of initial composition is oriented in the propagation direction of detonation (from left to right). Before entering the variable initial-state part of the channel, the detonation has been travelling a large distance in a uniform stoichiometric composition, which smoothly becomes non-uniform and leaner from the left of the soot foil. The detonation dynamics then depend on how rapidly the initial composition changes. The case of an abrupt change is given in Figure 7, top. The leftmost part of the soot foil shows that detonation cells have a practically constant mean width much smaller than the channel width and about equal to that associated with the CJ detonation in the initial stoichiometric composition. After about one third of the channel length, cells increase very rapidly and disappear before half of the length. In this strong-gradient situation, detonation quenches suddenly by means of a shock-flame decoupling mechanism. The case of a gradual composition change is given in Figure 7, bottom. The soot foil shows that the detonation cell mean width increases smoothly from its CJ value to values close to that of the channel width at about one third of the foil. A smooth transition from the multi-cell propagation mode to marginal propagation modes then takes place, with a very limited number of transverse waves. The transverse-wave number decreases as detonation propagates rightward in leaner compositions. In this weak-gradient situation, detonation quenches gradually by means of a smooth mechanism of transition from the quasi-1D, quasi-CJ multi-cell propagation mode to fully-3D unsteady marginal modes. This is an example of interplay between global effects from system boundaries and the local marginal propagation modes induced by changes in the initial composition.

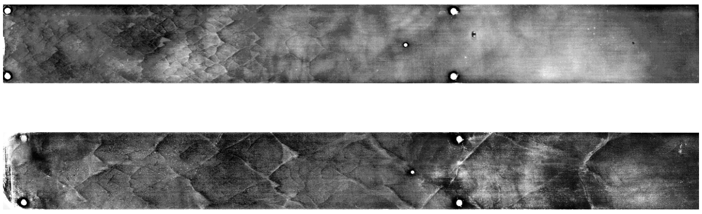


Figure 7 - Detonation quenching in a non-uniform composition contained in a square-section channel. Top: strong gradient. Bottom: weak gradient (Stephane Boulal, 2015)

Injector studies and RDE simulations with realistic injection conditions

Studies currently conducted at ONERA are aimed at applying rotating detonation to rocket propulsion, which is the most straightforward for the following reasons: i) the propellant mixture is concentrated and can easily detonate under the chamber conditions; ii) the engine mainly operates on a stable regime without strong variation of the global equivalence ratio and the chamber pressure; iii) integration of a detonation chamber in the engine architecture is not a critical point. In these studies, most attention is focused on the propellant injector because it is the key element of a detonation chamber.

Previous experimental and numerical studies have demonstrated RDE operation with various injector configurations, but the injector design was not a central point. Contrary to most known numerical simulations, in which fully premixed injection is mainly considered, propellants are always injected separately in the experiments for safety reasons.

At ONERA, we study various injector designs suitable for separate injection of gaseous propellants, trying to meet the following main requirements: i) fast and uniform propellant mixing; ii) limited pressure losses; iii) quick and efficient refilling of the chamber without excessive contact with burnt gases; iv) technological feasibility. The injector is assumed to be composed of a large number of identical injection elements regularly distributed over its face, as illustrated in Figure 8.

A special methodology has been devised enabling a single injection element to be analyzed, in order to model the operation of the entire injector. As the domain of interest is drastically reduced, large eddy simulations (LES) of the injected flow can be performed with fine resolution and at affordable cost. Thus, various geometrical configurations can be compared, in order to identify the optimum one.

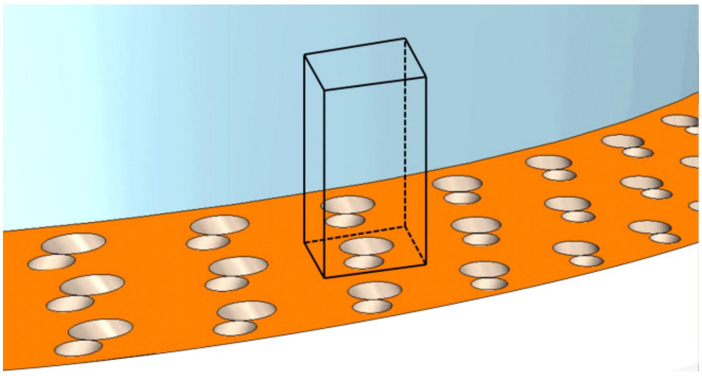


Figure 8 - Injection elements arranged in a regular pattern on the injector face. Black frame delimits a part of the chamber volume associated with a single injection element.

Using this methodology, a parametric study was first carried out by modeling the established injection of H_2 and O_2 in stoichiometric proportion [29]. By analyzing the simulated turbulent flow-fields, it was possible to identify the most efficient interaction between a pair of propellant jets, on the one hand, and the neighboring injection elements, on the other hand, providing the highest mixing efficiency.

As a second step, a transitory refill process after the detonation passage was simulated for a single injection element using a specific computational procedure [30], which enabled the mixture formation to be analyzed in detail and quantitatively characterized over time during the refill.

Since the latest publications [29]-[30], significant progress has been achieved in improving the injection element design. For the new injector design, a transitory refill process is illustrated in Figure 9, by LES results. The initial condition at $t = 0$ is obtained just after a detonation propagating in a uniform layer of fresh mixture. The development of a jet of fresh mixture during the gas expansion in the chamber is shown every 20 μs. Figure 9 shows the isothermal surface of 400 K surrounding the region filled with injected propellants, whereas its color indicates the mixture quality. Zero quality corresponds to fully unmixed propellants and unity corresponds to a stoichiometric composition not diluted by burnt gases. One can see that the propellants, being unmixed at the injector outlet, quickly mix in the chamber and occupy the volume attributed to the injection element at a short distance from the injector face. Zones of high mixture quality are observed from the very beginning of jet development, which means that the injection element operation is efficient during the whole refill process.

The final step in the injector design evaluation consists in rotating detonation simulation with many injection elements. In order to allow comparison with the idealized 2D simulation shown in Figure 9, the same main conditions are used in 3D simulations with 21 injection elements set in one row along the injection plane. Computational results from these simulations are presented in Figure 10, through the temperature fields in a mid-plane. Backflow is simulated in the admission lines but it cannot be shown for confidentiality reasons. The blocking time of the injection by the detonation products expansion represents up to 25% of the refill period. The first field shown in Figure 10a corresponds to the injection of a homogeneous premix of H_2 and O_2 in stoichiometric proportion. With respect to the 2D case, the mixture layer is no longer continuous, but rather composed of propellant jets surrounded by burnt gases. The jets have a slightly greater height than the 2D layer at the detonation front.

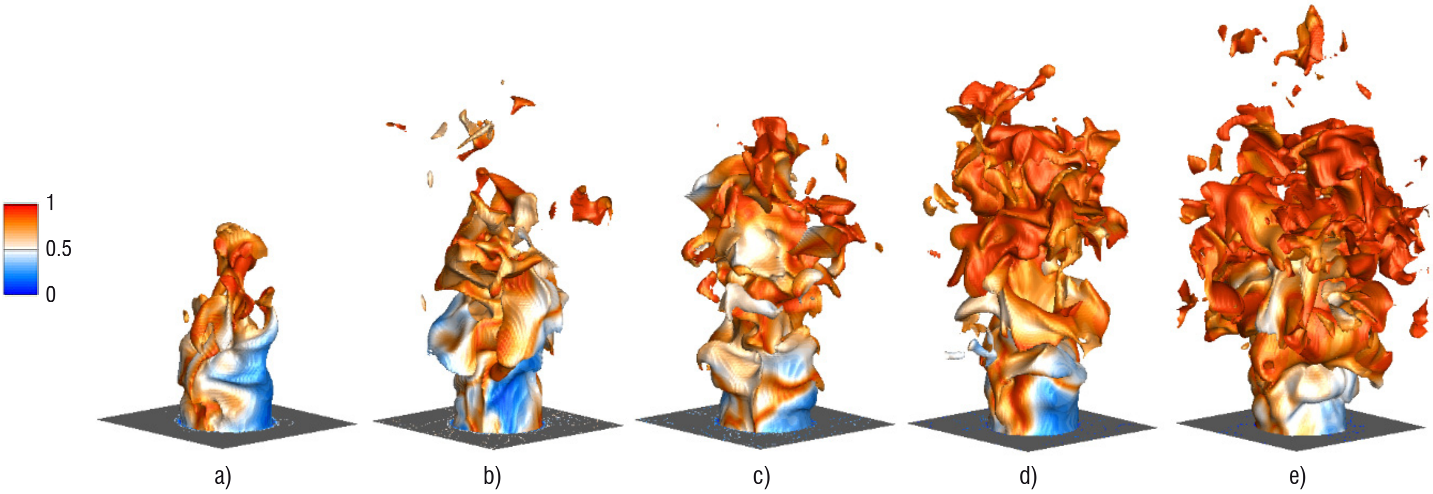


Figure 9 - Reinjection of the H_2-O_2 mixture after a detonation passage at different time instants: a) 20 μs ; b) 40 μs ; c) 60 μs ; d) 80 μs ; e) 100 μs. Isothermal surfaces of 400 K colored by mixture quality.

The detonation front is more perturbed as it propagates in a non-homogeneous layer and these perturbations produce a sequence of acoustic waves in the burnt gases, as can be seen in the field. This is not a realistic case because of the premixed injection, contrary to the second field shown in Figure 10b, which corresponds to the separate injection, keeping the global mass flow rates of H_2 and O_2 unchanged. Two main differences are observed between premixed and separate injection: the detonation front becomes more perturbed, as well as the whole flow-field; due to imperfect mixing in the jets, propellants are not completely burned by the detonation, but partially remain in small cold pockets that progressively dissipate and burn in the hot gases.

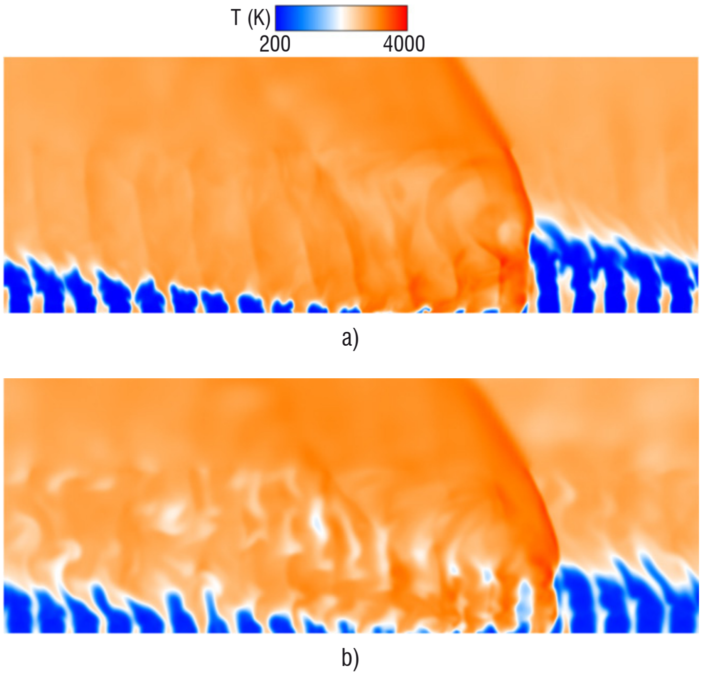


Figure 10 - Instantaneous temperature fields in a mid-plane from 3D simulations of a rotating detonation with 21 injection elements in a row: a) fully premixed injection, b) fully separate injection.

These are the very first results of 3D simulations with an improved injector design and realistic injection conditions. An important step towards an operational RDE design has been made compared to the simplified injection approach. Future studies include the evaluation of mixture heterogeneities to determine its effect on the detonation velocity and the chamber pressure, for instance.

Laboratory scale experimentation of rotating detonation

In the propulsion context, an experimental RDE device was designed and has been operated at PPRIME since 2003, within the framework of a feasibility project supported by CNES [9]. The experimental investigations led to the observations of the simultaneous stable rotation of 1 to 8 reactive fronts, depending on the injection conditions and the geometrical configurations. The global propulsive performance at sub-atmospheric and atmospheric pressures was evaluated on the basis of thrust and specific impulse measurements.

The RDE feasibility having been demonstrated, the current work is aimed at achieving a better understanding of the physics governing the complex flow field in an annular chamber and at providing the type and level of propulsive performance generated. Various RDE devices are currently under study.

In the first RDE device, the annular chamber currently being tested has an injection system enabling mass-flow rate operation up to 100 g/s. The inner diameter d_i of the chamber is 50 mm, with a channel width *e* of 10 mm. These new scales lead to a maximum specific mass flow rate, about 53 kg/(s m^2), which is close to the conditions used in several existing RDE chambers [10]. This experimental investigation is focused on the effect of the ratio (e/λ) on the detonation regime by varying the width λ of the detonation, since the width e of the annular chamber is maintained constant. The injection properties are

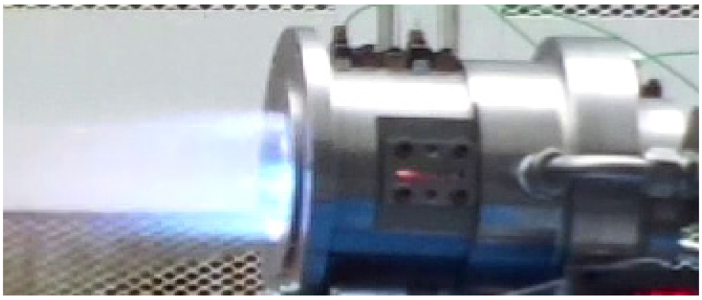


Figure 11 - Test in annular chamber

characterized by the mass-flow rate, equivalence ratio and pressure. The first results obtained with $C_2H_4/O_2/N_2$ stoichiometric mixtures with total mass flow rate of about 80 g/s show (Figure 11).

For a N_2 dilution corresponding to an oxidant composition with 30% of N_2, a deflagration is observed; the detonation cell size is about 10 mm. The ratio e/λ is lower than one.

For a N_2 dilution corresponding to an oxidant composition with 50% of N_2, a propagation of a reactive front is obtained with a main velocity of 1100 m/s. In this case, the width of the detonation cells is around 3 mm, the ratio e/λ is greater than one and $d_i < d_{min}$, where dmin is the minimum diameter given by dmin = 40λ and allowing steady detonation propagation [9].

The modular design of the second RDE device enables a large parametric study with a maximum mass-flow rate of 300 g/s to be carried out. These parameters concern the inner diameter d_i, the channel width *e*, various fuels and oxidizers, and the geometry of the injectors and nozzles.

Operational applications of RDE

For more than 12 years, MBDA has been actively developing technologies related to PDE and has led several R&T efforts in cooperation with French, Russian and Singaporean research institutions [13]. These efforts have been focusing on both rocket and airbreathing modes. Within the framework of this work, some specific studies have been performed to numerically simulate the DDT (deflagration to detonation) process in a pre-detonation tube; experimental work has been performed in cooperation with DSO (Singapore) and numerical results have been confirmed. This background has been used to design an operational ignition device for a RDE and has led to the development and demonstration of an efficient device (Figure 12).

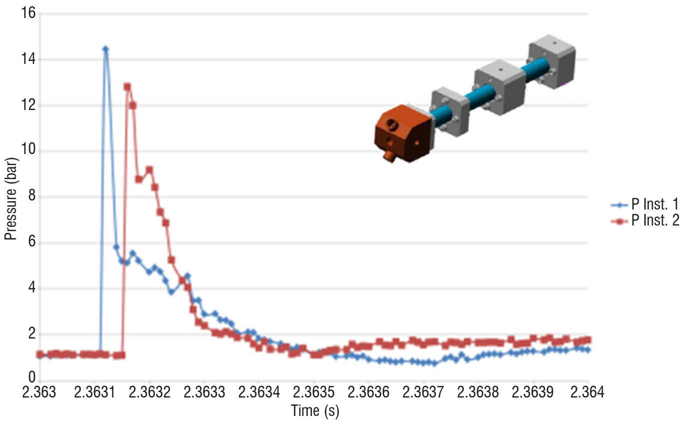


Figure 12 - Time evolution of the pressure at two points of the ignition device of an actual RDE

From 2002 to 2012, the objectives were to better understand RDE operation and address some key issues for an actual use as part of a propulsion system (Figure 13). This effort was mainly focused on the rocket mode, but some dedicated actions were taken with regard to airbreathing systems, including preliminary assessment of NOx production. A preliminary feasibility study of thermostructural composite fuel-cooled structure has been performed and some experiments in an actual detonation chamber have led to concluding results [26]. One specific characteristic of the RDE was also demonstrated during this program: the self-adaptation of the detonation to the fresh mixture local mass flow made it possible to achieve thrust vectoring by locally changing the injected mass flow rate (Figure 14).

Based on these studies and considering the growing interest shown around the world for the concept of RDE, a subscale demonstration engine was designed and manufactured in 2011 with the support of the Airbus Group Nursery [27]. This small demo was aimed, as a first step, at replicating experimental works performed at LIH. However, as a second step, it allowed enabled the test duration to be extended and the testing of the detonability of the H_2/CH_4 mixture. The

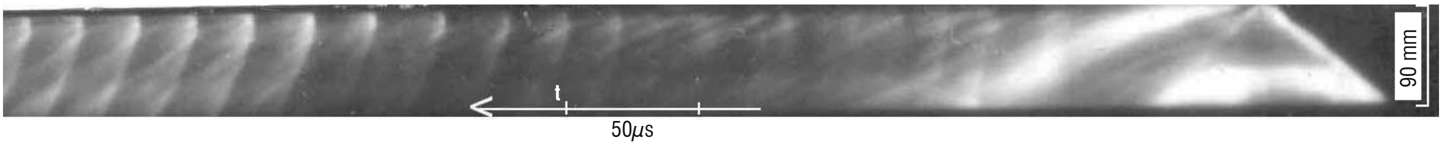


Figure 13 - Typical example of a high speed image acquisition done by LIH during RDE testing

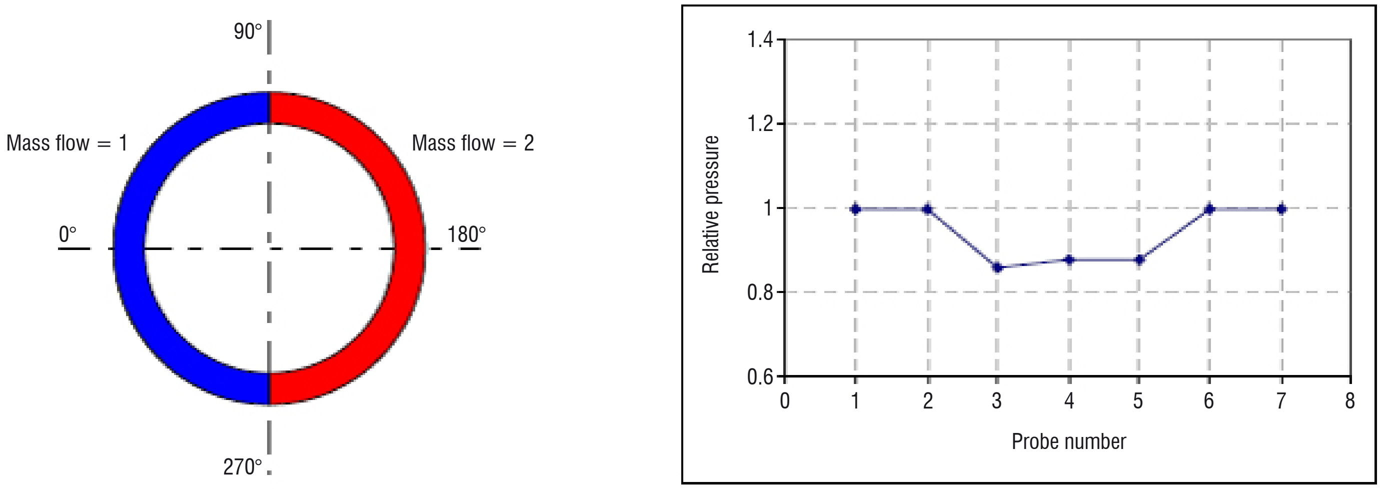


Figure 14 - Pressure evolution along the RDE circumference when varying the injected mass flow on each half of the chamber [24]

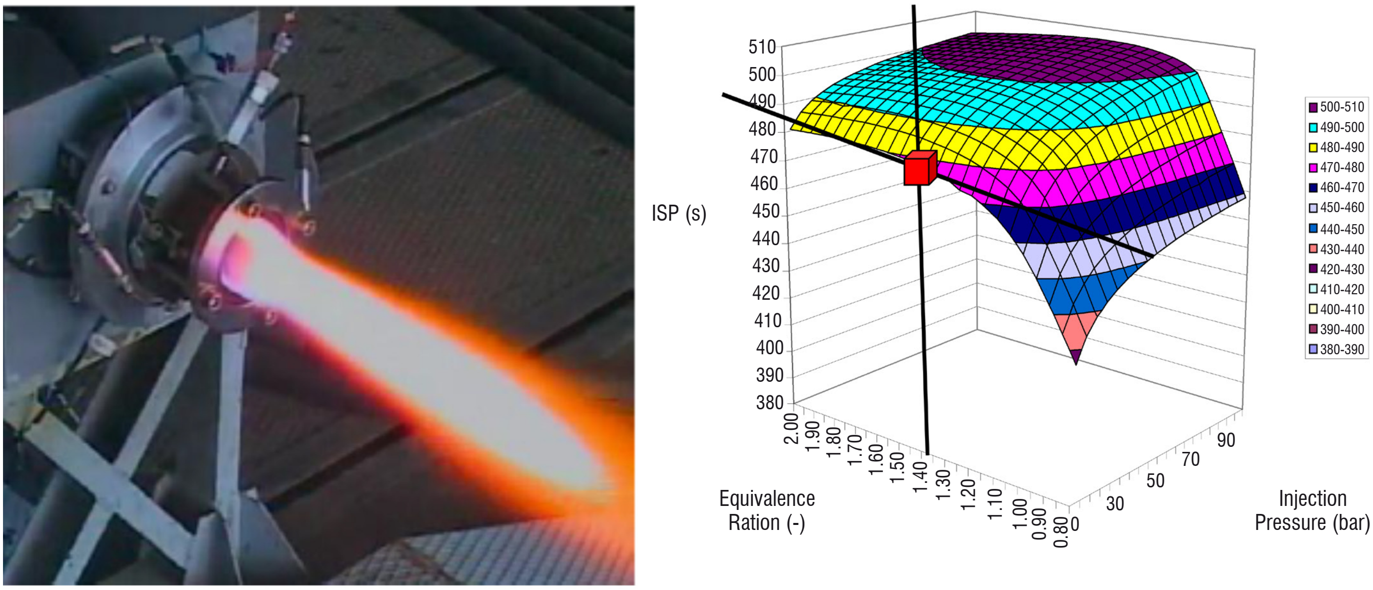


Figure 15 - RDE testing at MBDA and comparison of the test result (red cube) with the numerical prediction

annular chamber of the engine has inner and outer diameters of 80 mm and 100 mm. The test bench was equipped with force transducers enabling the thrust produced by the chamber when the detonation regime is established (Figure 15) to be measured.

The results were in line with theoretical estimations and helped to validate its in-house numerical models for the operation of a RDE. These models (0D, 1D and 2D) are daily used by MBDA to estimate performances and to design some future operational systems based on this new promising way of propulsion.

Today, based on several own patents related to RDE and with support from European FEDER funds and from Airbus Group Nursery, MBDA is developing a large scale test bench at Bourges-Subdray, dedicated to RDE.

Conclusion and perspectives

A huge reduction in the fuel consumption of future propulsive engines is an ambitious target set by the ACARE for 2050. Such a gain could be achieved only with a technological breakthrough. Two of the possibilities have been considered and are being investigated experimentally and numerically by MBDA France, ONERA, PPRIME and SAFRAN. Changing the actual thermodynamical cycle through Constant Volume Combustion or rotative detonation concepts could theoretically enable the target to be achieved.

To date, knowledge of the basic physical phenomena involved during combustion does not allow the potential profit of real propulsion engine using CVC or RDE combustion chamber to be quantified with good accuracy. Based on the first studies performed on specific prototypes by partners, for both CVC and RDE, the need for fundamental and basic research developments has been identified. Indeed, implementing such a concept requires the understanding and control of several basic phenomena that will jointly exist in a real engine, such as: the mixing process, ignition, dilution by residual burnt gas, and nonidealities. All of these phenomena must be considered under high-flow velocity and non-stationary conditions, whatever the concept (CVC or RDE). The combination of studies on elementary processes like the curvature effect on detonation dynamics, and on a reduced-scale or full-scale prototype, enables us to understand and model physical phenomena and highlight the potentialities of such concepts. The work carried out within the framework of the Chair CAPA, which started in 2015 for a period of 4 years, fulfills these main objectives.

Finally, in order to evaluate the final benefit of such concepts, integration tests should be performed considering a full engine composed of a compressor, a combustion chamber and a turbine when an air-breathing engine is considered, or a combination of a combustion chamber and a nozzle when a rocket application is targeted ■

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List of acronyms

CJ	*(Chapman-Jouguet)*
CPC	*(Constant-Pressure Combustion)*
CVC	*(Constant-Volume Combustion)*
CWDE	*(Continuous Wave Detonation Engine)*
PDE	*(Pulsed Detonation Engine)*
RDE	*(Rotating Detonation Engine)*

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