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Experimental and numerical study of cyclic variations in a Constant Volume Combustion chamber

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ABSTRACT

This paper describes a joint experimental and numerical study of a Constant Volume Combustion (CVC) chamber for propulsion engines. Combustion takes place in a constant volume vessel where gases are injected from a pressurized air inlet using valves. They are ignited using a spark and exhaust through a second set of valves. Like piston engines, CVC combustion raises multiple questions linked to the volumetric efficiency of the valves, the heat losses to the chamber walls, the ignition in a strongly turbulent flow, the influence of residual gases. These issues can compromise the potential gains associated to constant volume combustion. They are investigated in an experimental setup and compared to a full compressible LES. The major conclusion is the existence of significant cyclic variations which are observed in the experiment and analyzed in the LES: the local flow velocity at spark timing and the level of residuals are the major factors leading to cyclic variations. Cycles also appear to be coupled: combustion during cycle N directly affects cycle (N+1), more than in a piston engine.

1. Introduction

Constant Volume Combustion (CVC) is one of the thermodynamic cycles considered for future aeronautical engines because its cycle potentially offers a thermodynamic efficiency which is higher than what constant pressure combustion chambers can reach. Various technologies can be used to achieve a constant volume combustion, many of them based on supersonic combustion and detonation engines [1–3]. Another path is to rely on subsonic combustion in chambers using inlet and outlet valves (as in a piston engine) to ensure that combustion takes place in a constant volume vessel. Modern Diesel engines clearly demonstrate that constant volume combustion can lead to very high efficiencies. Whether such cycles can be applied to a gas turbine remains an open question.

Understanding flow and combustion processes in CVC chambers requires to tackle many daunting tasks which have been well identified in recent research [4,5] on LES of piston engines[1]:

- Since subsonic CVC devices use inlet and outlet valves, handling complex geometry and moving meshes is a necessity, thereby requiring specific solvers. Experimentally, this requires also a careful characterization of inlet and outlet feeding lines.
- CVC flows are clearly unsteady, going from intake phases at high speed to low speed combustion phases and high speed, high temperature exhaust phases. The combustion phase itself is dominated by turbulent processes and large-scale structures of the flow: turbulence during this phase is entirely created during the intake phase, calling for precise methods to evaluate turbulence and turbulent combustion processes. Large Eddy Simulation (LES) is the best option in this field [6–10]. Experimentally, all difficulties encountered in piston engines also appear here: multiple cycles are needed to perform averages, strong cycle-to-cycle variations make analysis complicated and require to use statistical methods. No direct comparison can be performed between individual cycles measured in the experiment or computed by the LES.
- Heat losses to walls are important and must be modeled adequately because they control the overall efficiency. Characterizing heat losses experimentally is also difficult because unsteady heat fluxes have to be measured locally [11].
- Chemistry plays a strong role and must be modeled with precision to capture both flame propagation and possible

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[1] A CVC chamber such as the one studied here, has many common aspects with a turbo-charged piston engine where the piston position would be fixed.

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reignition or autoignition events as well as wall quenching phenomena.

- In a piston engine, the turbulence created during the intake phase is dissipated during the compression phase. In a CVC chamber, the absence of compression phase also implies the ignition must be performed in a high velocity flow, leading to possible flame quenching as observed in intense turbulence flows [12,13].
- Controlling the ignition phase is more critical in CVC chambers than it is in gas turbines [14,15] because the spark timing also controls the efficiency: while, in the ideal cycle, combustion takes place in a closed volume, in the real world, valves have to be opened and closed at moments which do not necessarily allow combustion to go to completion, thereby letting fresh gases exhaust and leading to poor efficiencies if ignition events are not phased correctly with intake and exhaust valves. Providing reasonable models for ignition in LES [7,16–18] also remains a challenge because the plasma phases, which control ignition, are still out of reach of 3D simulation tools: in most models, these phases are simply neglected and replaced either by a local energy deposition or by the introduction of a sphere of burned gases at an arbitrary temperature when the ignition phase is supposed to be finished. Another difficulty is associated to the determination of the energy which is really released into the flow by the spark in the experiment [19–21]: very large losses are expected and only 10 to 30 percent of the spark energy is actually transferred to the flow even if a laser is used instead of a spark [22]. This large uncertainty on the exact energy to inject into the gas directly often leads to uncertain LES/experiments comparisons.

Of course, all these phenomena are coupled: the intensity of turbulence and the performance of the ignition system at the moment of spark ignition control the combustion speed and therefore the efficiency of the cycle. In piston engines, large-scale structures are destroyed during compression, thus creating small-scale turbulence that favors flame acceleration. For a CVC system to be efficient, combustion must be fast and this is the reason why detonation is often preferred. Here a subsonic CVC chamber is investigated, leading to flame speeds which are three orders of magnitude smaller than detonation velocities. Ensuring that combustion takes place sufficiently fast can be only obtained by maintaining high levels of turbulence. But when the combustion phase begins, valves must be closed (for combustion to proceed at constant volume) so that turbulence is already decaying and keeps decaying during the flame propagation. Imposing a very high initial turbulence at the moment when the inlet valves close may be a solution but in this case the ignition system may have difficulties igniting the flow reliably: misfires may occur. Like in a piston engine, the compromise between all these phenomena may lead to performances which are smaller than what the ideal CVC cycle was promising.

This paper presents a joint experimental / numerical study of flow and combustion processes in a subsonic CVC experiment installed at Institut PPRIME in Poitiers. LES is used to reproduce the experiment and analyse the various phases controlling the CVC operation over multiple cycles. The target configuration and the experimental results are presented in Section 2. The numerical method used for LES is described in Section 3. LES and experiments are first compared for non-reacting cases (Section 4) where the valves are operating and the flow is controlled by the pressure difference between the plenum and the outside atmosphere. Reacting cases are discussed in Section 5 which focuses on mechanisms leading to cyclic variations and describes an instability mechanism between cycles where cycle N directly affects the efficiency of cycle (N+1).

These instabilities lead to large variations between individual cycles which have to be understood and avoided. Combining experiments and LES is shown to be a good method to achieve these goals.

2. Experimental setup

The experimental system developed in PPRIME is based on an original combustor designed by COMAT, that features the successive phases of a CVC cycle (intake, combustion, exhaust) using patented rotary valves for intake and exhaust (french patent FR2945316 2009) (Fig. 1). The combustion chamber is a stainless steel vessel of inner volume 0.65 L, placed downstream of a carburation chamber, and followed by an exit duct to the atmosphere.

Combustor cycle

The operation of the combustor is governed by several events that occur successively during the cycle (Fig. 2), under supervision of a process controller. The symmetric geometry of the valves allows the succession of cycles every 180° of valve rotation (two full cycles per rotation); the rotation of the 4 valves is performed by a step motor at constant rotation speed $d\theta/dt$. The phasing between the inlet and outlet valves is defined by the angle ϕ between the crank angles where the exhaust and inlet valves are fully open respectively. During each cycle, the air–fuel mixture is prepared in the carburation chamber, introduced through the intake valves and spark-ignited inside the combustion chamber. Combustion propagates in the chamber before burned gases are ejected through the exhaust valves. The cycle exhibits a scavenging phase during exhaust, thus creating an intense flow from the carburation chamber to the exit duct.

The combustor is placed downstream of an air feed line that allows a precise control of the air flowrate F_{air}, including a compressor (400 g/s, 1.3 MPa), a regulation of temperature T_{air} (electrical heater TATT, 100 kW, up to 200 °C) and pressure P_{air} (dome pressure regulator IMF). Stagnation conditions are controlled in a 65 L isolated buffer tank placed between the feed line and the combustor in order to stabilize the upstream conditions of the combustor. The combustor is fueled with liquid iso-octane (VWR, $< 0.01\%$ water) through 8 injectors (Bosch EV14, SMD 200 μm) placed symmetrically in the carburation chamber (Fig. 1). Fuel injection for each cycle is performed in the carburation chamber sequentially: injectors 1 and 2 are activated first, followed by 3 and 4, 5 and 6, 7 and 8 (Fig. 2). Ignition is performed in the center of the chamber by a capacitive discharge ignitor (0–300 mJ) and a spark plug with tailored electrodes.

Diagnostics

Table 1 presents the diagnostics used in the experiment to measure: air flowrate F_{air}, air pressure P_{air}, air temperature T_{air}, wall temperature in the combustion chamber T_p. The controller allows to choose the cycle frequency f, the ignition crank angle θ_{igni} and the mass of fuel to be injected per cycle.

Time-resolved measurements are carried out to characterize the flow dynamics upstream of the combustor thanks to static pressure sensors placed in the carburation chamber (P_{adm}, Fig. 3) and in the combustion chamber (P_{cc}, Fig. 3).

These parameters are recorded using a high-speed acquisition device (Astromed TMX, 16 bit, 400 kHz). The propagation of the flame front is recorded by direct visualization of chemiluminescence using a high-speed color camera (Phantom v310, 3 kHz, 12 bit) and lateral and upper sapphire windows.