Influence of flow velocity on ignition stability in Constant Volume Combustion Chamber for air breathing propulsion

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Context and motivations to develop CVC for air breathing propulsion

Future ACARE constraints for 2050: -75% CO2 and -90% NOx emission (compared to the 2000 produced aircraft)

New concepts and breakthrough research: Pressure-Gain Combustion (PGC) by Constant-Volume Combustion (CVC)

Wintenberg and Shepherd, 2004 - AIAA
\[ \pi_c = 5 \quad T_i = 300K \quad p_i = 1\text{bar} \]
\[ C_3H_8 - \text{Air, ER} = 1 \]
Context and motivations to develop CVC for airbreathing propulsion

A few promising technologies to perform pistonless PGC:

- Internal combustion wave rotor: Purdue University 2000

- Shockless Explosion Combustion: TU Berlin 2014
**Context and motivations to develop CVC for airbreathing propulsion**

How to produce power in a turbo-engine using a CVC cycle?

Here are some of the specific issues raised by pistonless CVC:

- **system frequency** must be high to yield power: compared to Brayton cycle, combustion is unsteady and must occur within a defined time.


- Combustion efficiency: consumption of the fresh charge in a given volume and a given time, requires high flame speed.

- Enhance system stability: prevent from misfiring and cyclic fluctuation.
Since 2012 PPRIME is operating a **CVC prototype**: a combustion chamber with variable-section intake and exhaust systems.

First studies evidenced the operating domain of the combustor.

Recent work addressed the **fundamental phenomena** of interest:
- what parameters drive combustion propagation?
- what is the behaviour of ignition in CVC relevant conditions?
**Experiment and diagnostics**

**Combustor:**
Spark-ignited CVC chamber with intake and exhaust systems

**Diagnostics:**
- Combustion chamber: P, T, heat flux
- Air supply: P, T, mass flow rate
- Velocimetry: PIV
- High-speed color imaging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>0.65 L</td>
</tr>
<tr>
<td>Air flow</td>
<td>0–0.4 kg/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.1–0.4 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>$&lt; 150 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Ignition energy</td>
<td>30 mJ (spark)</td>
</tr>
<tr>
<td></td>
<td>300 mJ (spark+arc)</td>
</tr>
<tr>
<td>Port fuel injection</td>
<td>iso-octane (8 inj)</td>
</tr>
</tbody>
</table>

**Diagram:**
- Upper window
- Surface thermocouple $T_w$
- Pressure sensor $P_{doc}$
- Exhaust system
- Burnt gas
- Spark plug
- Inactive plug

**Experiment and diagnostics**
Experiment and diagnostics

**Intake and exhaust systems**
- Overall equivalence ratio
- Variable cross-section law (Valve1-Valve2)
- Variable phasing between intake and exhaust: $\phi$
- Influence on CVC phase duration (cycle frequency)

<table>
<thead>
<tr>
<th>Cycle frequency</th>
<th>$&lt; 100$ Hz</th>
</tr>
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<td>$\phi^*$</td>
<td>0 – 0.33</td>
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</table>

Aerodynamics ($<V>, V'$)
Blue flame: combustion of **premixed charge** fuel-air-burned gas

Highly **corrugated** flame front, stretched and convected by turbulent flow

Pressure evolution indicates combustion duration: a few ms

Peaks of wall heat flux: flame-wall interaction with successive reactive fronts

As a result, unsteady **thermal and mechanical loads**
Effect of operating parameters on combustion

Influence of **equivalence ratio** over maximum combustion pressure (as in piston engines)
For each initial pressure, the **optimum value** is obtained for the same equivalence ratio: maximum heat release and flame speed

Pressure and flame velocity **increase** with increasing ER*
Pressure and flame velocity **decrease** with increasing ER*

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**Internal aerodynamics**

**Time-resolved 2D-2C PIV**
- tomography in the median plane of the chamber
- oil seeded: visualization of the flame front
- velocity field is measured in the fresh gases
- 10 kHz acquisition
- 0.65 mm resolution
**Internal aerodynamics**

**Velocity field decomposition method**
Method inferred from Reuss et al. (1989), Boust et al. (2007)

\[
U(x, y, t, i) = \langle U(x, y, t, i) \rangle_i + U(x, y, t, i)_{LF} + U(x, y, t, i)_{HF}
\]

- Velocity
- Average
- Cyclic fluctuation
- Turbulence

\[ t^* = 0.6 \]

\[ \langle V \rangle \sim 50 \text{ m/s} \]

\[ \langle u' \rangle \sim 20 \text{ m/s} \]
**Internal aerodynamics**

Ensemble-averaged velocity field: overall flow structure

Asymmetric vortices

$t^*$ values shown for different time intervals.
Internal aerodynamics

Velocity field decomposition of a reactive cycle

Free decay of velocity $|V|$ and turbulence $(u', v')$ occurs once pressure equilibrium is achieved

$t^* = 0.6$
$t_{ign}^* = 0.78$
Aerodynamics modification induced by variation of exhaust cross-section law and phasing $\phi$

- Opening duration of exhaust valve is reduced
- Scavenging could be the same or reduced by changing the phasing between intake and exhaust: $\phi$
Aerodynamics modification induced by variation of exhaust cross-section law and phasing $\phi$

Ignition rate in function of the phasing for a given cycle frequency and a given ignition delay (25Hz, $t_{\text{ignition}}^*$ = 0.69)

Ignition rate in function of the ignition time for a given cycle frequency and a given phasing (40Hz, $\phi^*$ = 0.25)
Ignition success is critical for engine reliability, stability.

Ignition probability is firstly investigated at two ignition positions (C) and (F) with equal discharge energy (30 mJ):

<table>
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<th>Ignition point</th>
<th>Ignition probability</th>
<th>$t_c^*$</th>
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<tr>
<td>Point F</td>
<td>48.3%</td>
<td>0.88 ± 0.12</td>
</tr>
<tr>
<td>Point C</td>
<td>65.4%</td>
<td>1.0 ± 0.16</td>
</tr>
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**Ignition stability**

Misfiring can be due to high flow velocity through flame stretch or kernel blow-off ($E_{\text{discharge}} \sim 30\text{mJ}$)

Ignition success is correlated directly to **local velocity** ($\sim 25\text{m/s threshold}$)

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Large eddy simulation performed by Labarrere et al. allows to identify a critical velocity for ignition of 33 m/s for ignition energy corresponding to around 200 mJ.
Ignition stability

Estimation of the ignition rate for the given energy considered by Labarrere (LES). Tests have been performed for the same higher ignition energy.

Experimental ignition probability is 100% for the given energy released during spark discharge.
Phenomena coupling on ignition stability

However, velocity is not the only parameter that controls misfiring. Indeed, Large eddy simulation has shown one coupling between local flow velocity and residual burned gases rate. When a misfiring is observed, velocity is high but burned gases rate is larger. In the set up, mixing and flow velocity are correlated. As experimental determination of local burned gases rate is very difficult to perform, numerical and experimental approaches have to be combined to identify the respective influences of both parameters;

Conclusion

- One optimum phasing exists for a given chamber geometry/Mixture/Ignitor. It is also the case for the cycle frequency.

- Ignition stability is strongly linked to local instantaneous velocity.

- Changing one physical parameter of the setup (cross-section law, cycle frequency, ...) induces strong changes on flow characteristics (velocity, turbulence) and mixing process that affect directly the ignition stability.

- In comparable CVC systems, burned gas ratio is directly correlated to flow motion.

- In such complex configuration crossing numerical-experimental approaches is essential to understand coupling of elementary processes that usually affect ignition and combustion propagation.

- Experimental database is available at PPRIME concerning ignition stability and combustion processes in various conditions.
Thank you for your attention

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