Ignition dynamics

- Ignition of a homogeneous reactor
- Ignition under non premixed conditions
- Light round in an annular combustor
Ignition of a homogeneous reactor

The adiabatic reactor contains a homogeneous reactive mixture at an initial temperature $T_0$ with initial mass fractions $Y_{F0}$ and $Y_{O0}$.

It is assumed that a single step reaction takes place

$$\nu'_F F + \nu'_O O \rightarrow P$$

with a reaction rate following Arrhenius kinetics

$$\dot{\omega} = B C_F C_{O2} \exp\left(-\frac{E}{RT}\right)$$

Species concentrations may be written in terms of mass fractions

$$C_F = \rho Y_F / W_F, \quad C_O = \rho Y_O / W_O$$

The reaction rate becomes

$$\dot{\omega} = \frac{B \rho^2}{W_O W_F} Y_O Y_F \exp\left(-\frac{E}{RT}\right)$$
The ignition is governed by a first order differential equation together with algebraic expressions for the fuel and oxidizer mass fractions

$$
\rho c_v \frac{dT}{dt} = (-\Delta E) \dot{\omega}
$$

$$
\dot{\omega} = \frac{B \rho^2}{W_F W_O} Y_F Y_O \exp\left(-\frac{E}{RT}\right)
$$

$$
Y_F = Y_{F0} - c_v \frac{\nu'_F W_F}{(-\Delta E)} (T - T_0)
$$

$$
Y_O = Y_{O0} - c_v \frac{\nu'_O W_O}{(-\Delta E)} (T - T_0)
$$

An asymptotic analysis based assuming a large activation energy indicates that the perturbation of temperature with respect to the initial temperature is governed by the following differential equation

$$
\frac{dT}{dt} \left(\frac{T_1}{T_0}\right) = \frac{(-\Delta E) B \rho}{\varepsilon W_F W_O c_v T_0 Y_{F0} Y_{O0}} \exp\left(-\frac{E}{RT_0}\right) \exp\left(\frac{T_1}{T_0}\right)
$$

where \( \varepsilon = \frac{RT_0}{E} \) is a small parameter

This expression features a characteristic time

$$
t_i = \frac{RT_0}{E} \left(\frac{c_v T_0}{(-\Delta E) B \rho Y_{F0} Y_{O0}} \frac{W_F W_O}{\exp\left(\frac{E}{RT_0}\right)}\right)
$$
Inserting this definition in the differential equation for the temperature perturbation one finds

\[ \frac{d(T_1/T_0)}{d(t/t_i)} = \exp\left(\frac{T_1}{T_0}\right) \]

The temperature perturbation features a logarithmic behavior

\[ \frac{T_1}{T_0} = -\ln(1 - \frac{t}{t_i}) \]

When \( t << t_i \) the perturbation in temperature is small. When \( t \) approaches \( t_i \) this perturbation increases without bound.
Combustor

Non-premixed multiple injector combustor

Stable operation

Extinction by pressure waves

Spark plug

Propane

Frequency doubler

CCD camera

Injector

Mirror

Laser sheet

Nd:YAG laser

Dye laser

Cylindrical lenses

Laser induced fluorescence of OH
Ignition of the multiple injector combustor (imaging by laser induced fluorescence of OH)

Direct simulation of ignition in homogeneous turbulence (T. Poinset)
A pioneering LES of ignition in a gas turbine configuration

$t = 14\,\text{ms}$

$t = 29\,\text{ms}$

$t = 19.2\,\text{ms}$

$t = 46\,\text{ms}$


Ignition dynamics in annular combustors

CFM 56 turbofan

Annular chamber

Annular geometry

Multiple swirled injectors

Liquid phase injection (kerosine /air)

High pressure

Annular combustor MICCA2

16 swirled injectors

Chamber

Quartz tubes

Spark plug

Plenum

Annular geometry

Multiple swirled injectors

Premixed (propane/air)

Atmospheric pressure

Annular combustor MICCA-Spray

200 mm

Annular geometry

Multiple swirled injectors

Liquid injection (heptane/air)

Atmospheric pressure
Ignition dynamics in an annular combustor

High speed imaging
Frame rate
\( f_c = \frac{1}{6000}\ s \)
Exposure duration
\( \tau = 16.6\ \mu s \)

Operating point
Bulk injection velocity
\( U_b = 12.2\ m/s \)
Equivalence ratio
\( \phi = 0.76 \)
Thermal power
\( P_{th} = 40\ kW \)


Light round ignition of the MICCA2 combustor

MICCA2 under nominal operation

Light round ignition of the MICCA combustor. Experiment and simulation.

\[ U_b = 18 \text{ m s}^{-1} \]

Light round ignition of the MICCA combustor. Experiment and simulation.

\[ U_b = 24 \text{ m s}^{-1} \]

Flame fronts merging delay as a function of the bulk injection velocity. The magenta star symbols stand for the time lags determined from LES calculations.
Light round ignition in MICCA-Spray

$C_3H_8$ Propane/air premixed

$C_7H_16$ Heptane/air spray injection

$C_{12}H_{26}$ Dodecane/air spray injection

Filmed at 6000 fps, slowed down at 24 fps


Flame and spray dynamics during the light-round process in an annular system equipped with multiple swirl spray injectors

Kevin Prieur, Daniel Durox, Guillaume Vignat, Thierry Schuller, Sébastien Candel

Experimental Study of Ignition in Laboratory Scale Annular Combustors

Swirled Injector forms a Hollow Cone Spray C\textsubscript{7}H\textsubscript{16}/Air

Impact of Fuel Volatility on the Light-Round Ignition Time in MICCA-Spray


MICCA: An Annular Laboratory Scale Combustion Chamber

Steel tube used as inner wall to show the wall temperature distribution and illustrate the position of the flames.
MICCA-Spray: An Annular Combustion Chamber with Swirl Spray Injectors

16 injectors

- Main Body
- Liquid Fuel Atomizer
- Swirler
- Outlet Cone
- Backplane Injector Outlet

- Liquid n-heptane

- Simplex atomizer
- Hollow cone spray
- n-heptane droplets
- Spray cone

\[ d_i = 8 \text{ mm} \]
\[ u_{bulk} = \frac{4\pi n}{\pi \rho_0 d_i^2} \]
\[ d = 3 \text{ mm} \]
\[ R_0 = 5 \text{ mm} \]

A-B: horizontal laser sheet
C: vertical laser sheet
Steps of the ignition process in an annular combustor

- Initiation of a hot gas kernel by the spark
- Expansion of the kernel leading to the ignition of the first injector
- Creation of two flame branches
- Propagation of these branches
- Flame merging

**MICCA-Spray: Light-Round Process**

- n-heptane (liquid) / air
- Equivalence ratio: 0.89
- Bulk velocity: 31 m/s
- Thermal power: 80 kW

**MICCA-Spray: Travelling Flame Branch**

- Preheated combustor walls (870 K)
- Single spark plug ignition
- Central steel plate
  - A single flame branch is filmed.
- n-Heptane (liquid) / Air
- \( \phi = 0.89 \)
- \( u_{\text{bulk}} = 31 \text{ m s}^{-1} \)
- \( P = 80 \text{ kW} \)

Phantom v2512
- 6 000 fps, 1280x800 pixels, Exposure \( \Delta t = 166 \mu s \)
- 400 – 470 nm filter for CH* emissions
The volumetric expansion of the burned gases drives the movement of the flame. Zone I: Close to the backplane, velocity mainly in the azimuthal direction, 

$$v_\theta \approx 15 - 20 \text{ m s}^{-1}$$

Zone II: Both azimuthal and axial components, $v_\theta \approx v_z$ and $\|v\| \approx 10 - 15 \text{ m s}^{-1}$. 
MICCA-Spray: Changes in Flame Shape during the Light-Round Process

The ignition process is repeated several times. Transition from Shape A to Shape B in approximately $\tau_s = 40\,\text{ms}$. 

Abel transform

Direct CH* emission imaging

5 ms 21 ms 37 ms 53 ms 69 ms 85 ms
True-color low-speed images of the light-round in the MICCA combustion chamber under premixed propane-air conditions with $\phi = 0.76$ and $P = 60$ kW.

SICCA-Spray measurements

Velocity $u(t)$ and flame luminosity $l(t)$ signals during ignition of the single SICCA-Spray injector. The black-dotted line corresponds to the mean velocity at nominal operating conditions.
Pressure perturbation associated with the rate of change of heat release is given by

\[ p'(r, t) = \frac{\gamma - 1}{4\pi c_0^2} \int_V \frac{1}{|r - r_0|} \frac{\partial}{\partial t} \dot{Q}'(r_0, t - |r - r_0|/c_0) dV(r_0) \]

The heat release occupies a compact region. One may use the heat release rate integrated over the whole region

\[ p' \approx \frac{\gamma - 1}{4\pi c_0^2} \frac{1}{r} \frac{d\dot{Q}'}{dt} \]

In principle this expression is only valid in the farfield but it has been used under similar conditions with some success to estimate near field pressure perturbations (for example by Noiray et al)
To get the rate of change of heat release rate one uses

\[ \Delta \dot{Q}' \simeq (80) \left(10^4\right) W \quad \Delta t = 4 \times 10^{-3} \text{ s} \]

(results of calculations by Thea Lancien)

\[ \frac{d \dot{Q}'}{dt} \simeq \frac{(80) \left(10^4\right)}{(4) \left(10^{-3}\right)} = 200 \text{ MW s}^{-1} \]

\[ p' \simeq \frac{0.4}{4\pi (340)^2} (2)(10^8) \frac{1}{r} \quad p' \simeq 55.07 \frac{1}{r} \]

For \( r = 0.02 \text{ m} \) \quad \( p' \simeq 2750 \text{ Pa} \)

The pressure disturbance induced by the rate of change of the heat release rate is of the order of 3000 Pa

Injector head loss

\[ \Delta p = \frac{1}{2} \sigma \rho u_0^2 \]

Model M1

\[ \tau \frac{dv_*}{dt} + \frac{1}{2} v_*^2 = \frac{1}{2} + \frac{\Delta p'}{\sigma \rho u_0^2} \]

Model M2

\[ \frac{1}{\omega_0^2} \frac{d^2 v_*}{dt^2} + \tau \frac{dv_*}{dt} + \frac{1}{2} v_*^2 = \frac{1}{2} + \frac{\Delta p'}{\sigma \rho u_0^2} \]
Velocity obtained at the hot wire position using model M1 (blue) and M2 (red). The velocity measured by the hot wire is shown as a thin black line. The pressure perturbation used for the present calculation is shown as a thicker black line on top, associated with the right axis.