Combustion for aerospace propulsion: progress and challenges

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MUSAF II, Toulouse
September 18-20, 2013

- Many thanks to Thierry Poinsot and to the scientific committee of MUSAF for inviting me to give this lecture
- It is has been a pleasure to prepare this talk and an even greater one to share it with you
- In this review, I'll underline a few of the recent developments in combustion and their application to propulsion
- To cover such a broad subject one would need a couple hundred slides and a few hours. It was heartbreaking to throw away a lot of interesting material to remain within the time allocated

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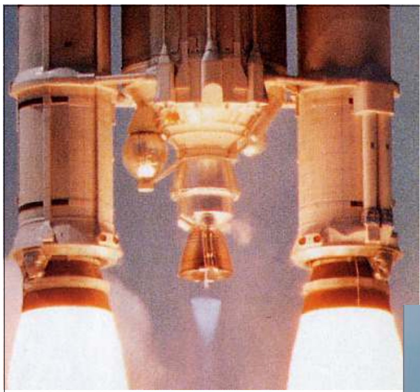
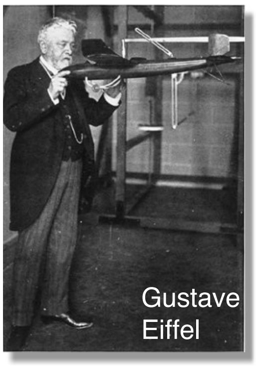


- Background
- Issues in combustion
- Combustion for aeronautics
- Combustion for space propulsion
- Conclusions

Ecole Centrale Paris alumni aviation pioneers



Gustave Eiffel

- **Gustave Eiffel** carries out pionnering experiments on wing and aircraft aerodynamics. He receives the second Langley medal in 1917

- **Louis Blériot** crosses the English channel with his Blériot XI on July 25, 1909, 6 years after the Wright brothers first flight and wins the Daily Mail prize

The Blériot XI flies at Le Bourget in 2009

- On February 24, 1954, at the controls of a Mystere IV, **Constantin Rozanoff** is the first French pilot to break the sound barrier with a Dassault aircraft

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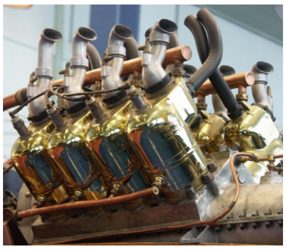
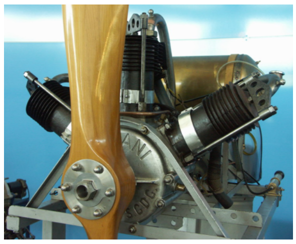
Engines make the difference

Louis Blériot crosses the English channel in his Blériot XI on July 25, 1909

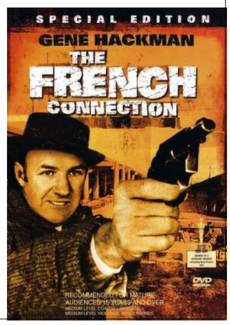


Antoinette engine 50 hp designed by Léon Levavasseur



Anzani engine 3 cylinders 25 hp chosen by Blériot to cross the channel

With a power per unit mass double that of the engines available elswhere, France had at the end of 1906, **the best engines in the world**, allowing the remarkable progress of its aviation in 1908 et 1909.



F.E.C. Culick «Aeronautics, 1898-1909 : The French American Connection » presented at *the American Society for the History of Technology*, 1987

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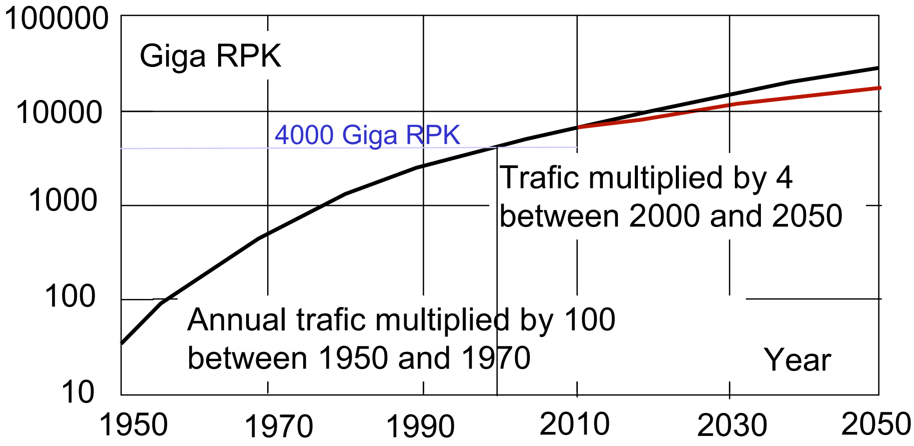
About 100 years after : more than 4000 billion Revenue Passenger-km/yr

RPK : Revenue passenger-kilometer



Adapted from G. Ville (ECP 2009)

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«… one can double the trafic but without doubling the nuisances… »

Jean-Paul Herteman
CEO, Safran

- Trafic increase
- Environmental impact
- Aircraft fleet renewal short haul and mid-range transport
- Emergence of new manufacturers

- Optimized architectures : augmented compression ratio, bypass ratio, turbine inlet temperature
- More efficient, less polluting technologies
- New materials, new concepts
- Novel configurations

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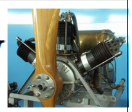
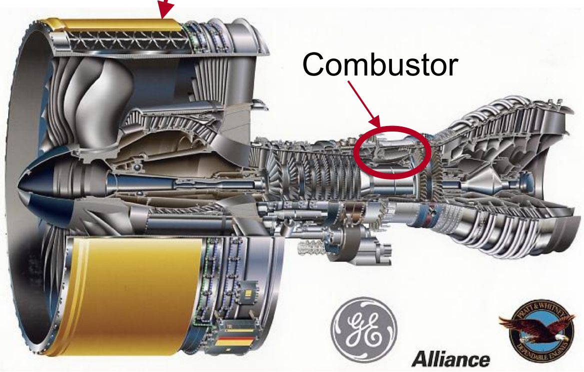
Technological, scientific and economic challenges

$\simeq 100$ years



$P = 18\,\mathrm{kW}$

High bypass ratio engines (GP7270)



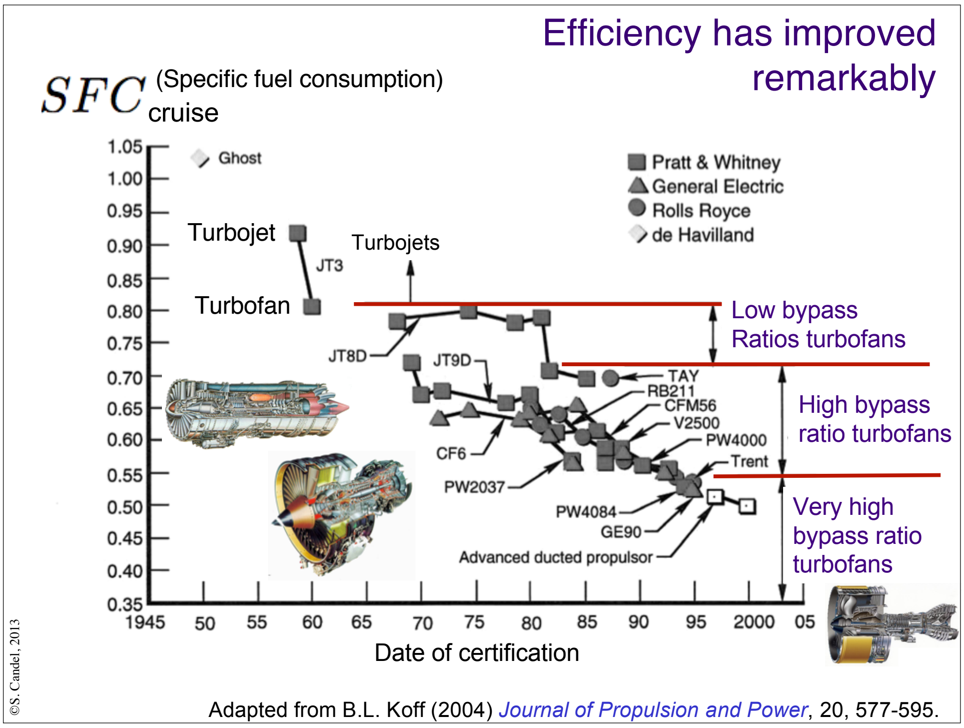
$$\alpha = \frac{\dot{m}_F}{\dot{m}_C} = 9$$

$$\dot{m}_a = 540\,\mathrm{kg\ s^{-1}}$$

$$\dot{m}_f = 10\,\mathrm{kg\ s^{-1}}$$

$$P = 400\,\mathrm{MW}$$

$$P/V \simeq 4\,\mathrm{GW\ m^{-3}}$$


Efficiency has improved remarkably
SFC (Specific fuel consumption) cruise
Ghost
Pratt & Whitney
General Electric
Rolls Royce
de Havilland
Turbojet
Turbofan
JT3
Turbojets
JT8D
JT9D
Low bypass Ratios turbofans
High bypass ratio turbofans
Very high bypass ratio turbofans
TAY
RB211
CFM56
V2500
PW4000
Trent
CF6
PW2037
PW4084
GE90
Advanced ducted propulsor
Date of certification
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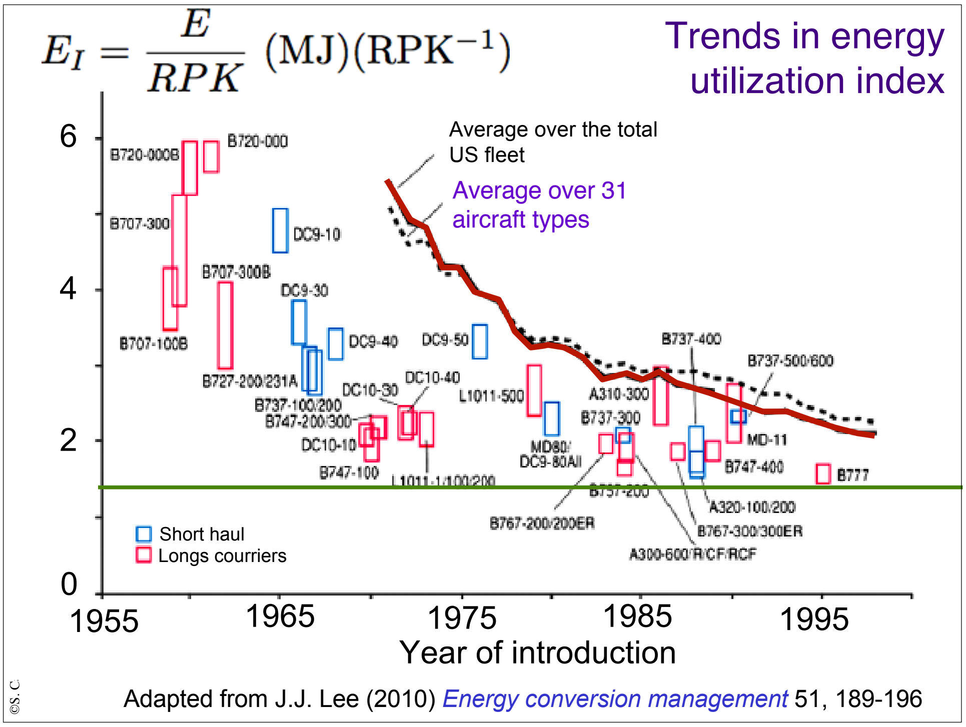
Adapted from B.L. Koff (2004) Journal of Propulsion and Power, 20, 577-595.


$E_I = \frac{E}{RPK}$ (MJ)(RPK^{-1})
Trends in energy utilization index
Average over the total US fleet
Average over 31 aircraft types
Short haul
Longs courriers
Year of introduction
©S. C
Adapted from J.J. Lee (2010) Energy conversion management 51, 189-196

Numerical values are easier to understand if they are expressed in liters of kerosene per 100 km per revenu passenger (at least on this side of the Atlantic ocean)

$$E_I = 1.5\,\mathrm{MJ\ RP^{-1}\ km^{-1}}$$

$$E(100\,\mathrm{km}) = 150\,\mathrm{MJ\ RP^{-1}}$$

Mass of kerosene required per 100 km

$$m_f(100\ \mathrm{km}) = \frac{150}{42} = 3.57\,\mathrm{kg}$$

Kerosene density is $\rho = 800\,\mathrm{kg\ m^{-3}}$

$$V_f(100\,\mathrm{km}) = 4.46\,\mathrm{l\ RP^{-1}}$$

$$50\,\mathrm{Miles\ RP\ Gal^{-1}}$$

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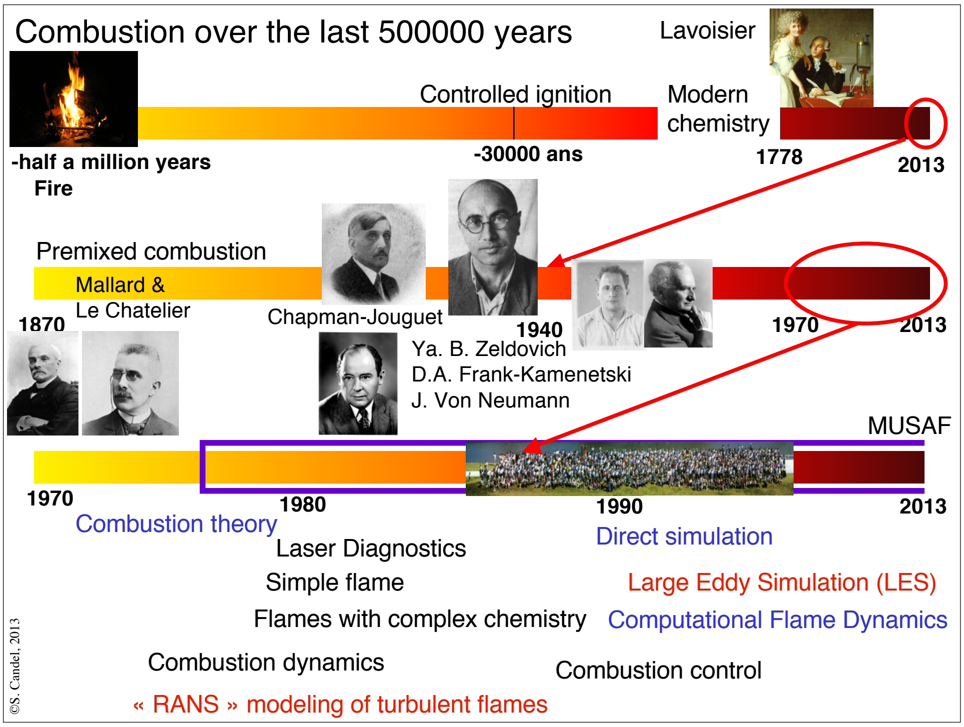

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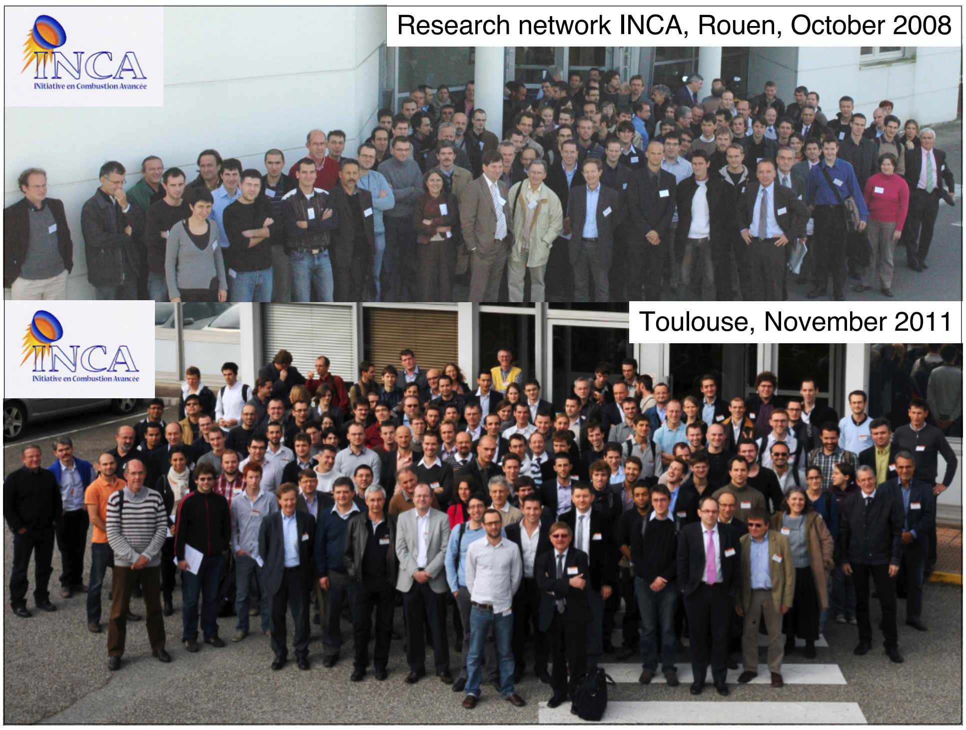
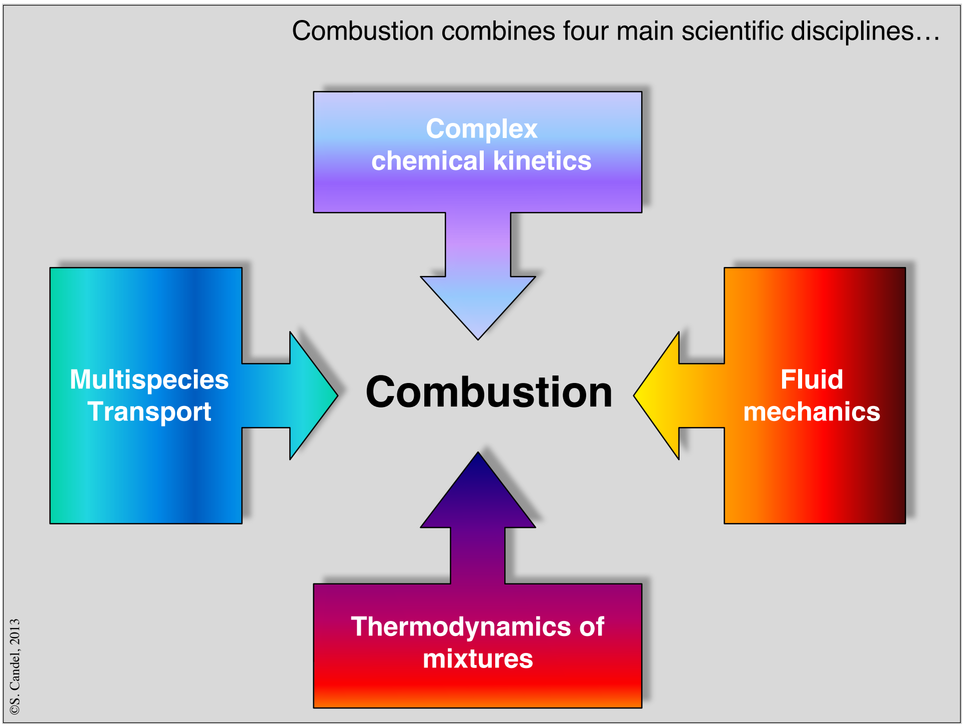

Research network INCA, Rouen, October 2008
INCA
Toulouse, November 2011
INCA


Combustion combines four main scientific disciplines…
Complex chemical kinetics
Multispecies Transport
Combustion
Fluid mechanics
Thermodynamics of mixtures
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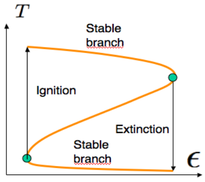
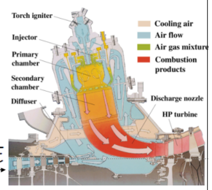
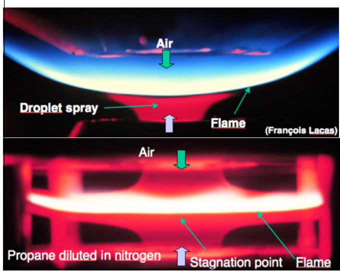
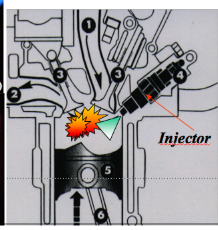
….and raises many difficult issues

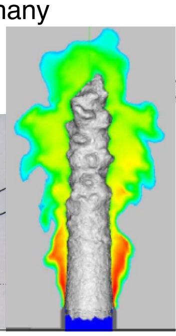
(1) Many modes of combustion, configurations, geometries and operational conditions
(2) Complex kinetics
(3) Stiff reaction rates (Arrhenius laws) $k_f = BT^\beta \exp(-\frac{E_a}{RT})$
(4) Thin layers and multiscale problems
(5) Critical conditions (ignition, extinction…)
(6) Reactants injected in liquid or solid form
(7) Interactions with boundaries
(8) High pressure, transcritical conditions
(9) Complex turbulent flows
(10)Essentially multiphysics (coupling with many other processes : acoustics, radiation…)

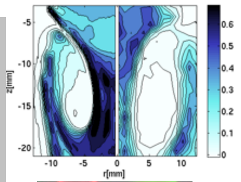


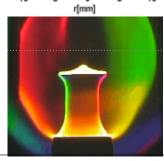






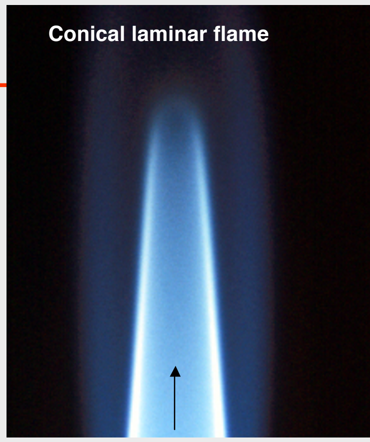






Issue 2 : Combustion involves complex chemical kinetics

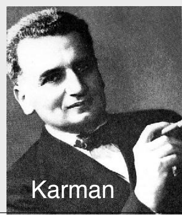
Chemical conversion takes place through a large number of elementary reactions (40 species and more than 120 reactions for a propane/air flame)

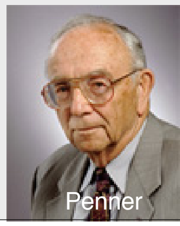


Premixed air/propane

In 1954 Karman and Penner were treating the ozone flame by means of a two step reaction model

$$O_3 + M \rightarrow O + O_2 + M$$
$$O + O_3 \rightarrow 2O_2$$





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FUNDAMENTAL APPROACH TO LAMINAR FLAME PROPAGATION

THEODORE VON KARMÁN and S. S. PENNER*

Advisory Group for Aeronautical Research and Development,
NATO, Palais de Chaillot, Paris 16, France

The complete system of equations for a theory of laminar flame equations is presented, taking into account both heat conduction and diffusion, for the case of an arbitrary number of simultaneous reactions. The eigenvalue problem determining the flame velocity is formulated. Two examples are given in order to show that explicit analytical expressions for the flame velocity can be obtained, which are in good agreement with the results obtained by numerical integration of the equations. In the first example (hydrazine decomposition) one reaction is considered as global, i.e., rate-controlling, reaction. In the second example
(ozone decomposi
radical O, whic
classical chemic
obtained for the
making drastic
flame has a beari
in general. Th
plicated chain re

…The method indicated in this paper gives hope that the more complicated chain reactions, such as the combustion of hydrocarbons, will also be made accessible to theoretical computation.

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Th. von Kármán, **S. S. Penner**, Fundamental approach to laminar flame propagation, *in: Selected Combustion Problems*, Part 1, Butterworths Scientific Publications, London, 1954, pp. 5–41.

Nb	Reaction	B	b	E
1	$H_2 + O_2 \rightleftharpoons 2OH$	1.70E+13	0.000	47780
2	$OH + H_2 \rightleftharpoons H_2O + H$	1.17E+09	1.300	3626
3	$H + O_2 \rightleftharpoons OH + O$	2.00E+14	0.000	16800
4	$O + H_2 \rightleftharpoons OH + H$	1.80E+10	1.000	8826
5[a]	$H + O_2 + M \rightleftharpoons HO_2 + M$	2.10E+18	-1.000	0.
6	$H + O_2 + O_2 \rightleftharpoons HO_2 + O_2$	6.70E+19	-1.420	0.
7	$H + O_2 + N_2 \rightleftharpoons HO_2 + N_2$	6.70E+19	-1.420	0.
8	$OH + HO_2 \rightleftharpoons H_2O + O_2$	5.00E+13	0.000	1000.
9	$H + HO_2 \rightleftharpoons 2OH$	2.50E+14	0.000	1900.
10	$O + HO_2 \rightleftharpoons O_2 + OH$	4.80E+13	0.000	1000.
11	$2OH \rightleftharpoons O + H_2O$	6.00E+18	1.300	0.
12[b]	$H_2 + M \rightleftharpoons H + H + M$	2.23E+12	0.500	92600
13	$O_2 + M \rightleftharpoons O + O + M$	1.85E+11	0.500	95560
14[c]	$H + OH + M \rightleftharpoons H_2O + M$	7.50E+23	-2.600	0.
15	$H + HO_2 \rightleftharpoons H_2 + O_2$	2.50E+13	0.000	700.
16	$HO_2 + HO_2 \rightleftharpoons H_2O_2 + O_2$	2.00E+12	0.000	0.
17	$H_2O_2 + M \rightleftharpoons OH + OH + M$	1.30E+17	0.000	45500
18	$H_2O_2 + H \rightleftharpoons HO_2 + H$	1.60E+12	0.000	3800
19	$H_2O_2 + OH \rightleftharpoons H_2O + HO_2$	1.00E+13	0.000	1800

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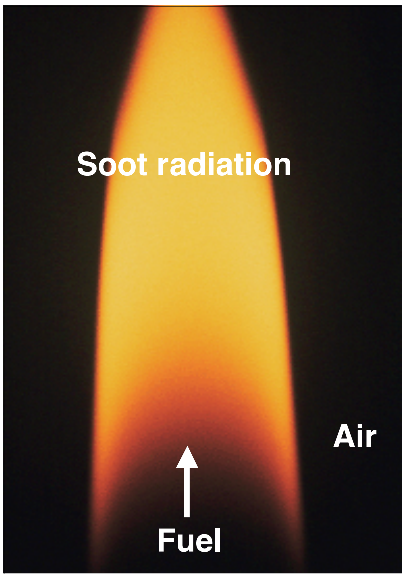
Reaction mechanism for hydrogen/air oxidation
9 species, 38 reactions

$$k_f = BT^b \exp(-\frac{E}{RT})$$



Non-premixed propane/air flame

Issue 3 : Reaction rates follow Arrhenius laws. Problems are mathematically stiff

$$k_f = BT^\beta \exp(-\frac{E_a}{RT})$$

Sven August Arrhenius

Jürgen Warnatz

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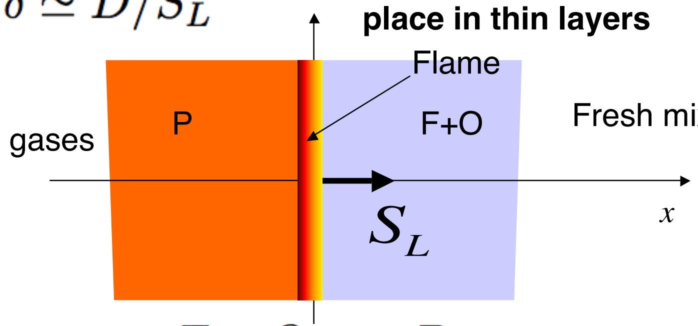
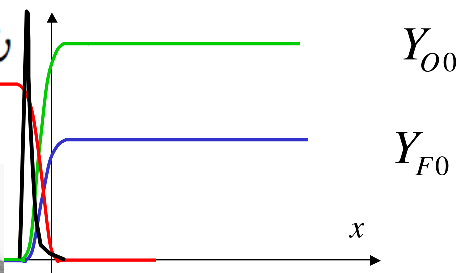
Issue 4 : Combustion takes place in thin layers

$$\delta \simeq D/S_L$$



$$F + O \longrightarrow P$$



Zeldovich Frank-Kamenetski Williams Clavin

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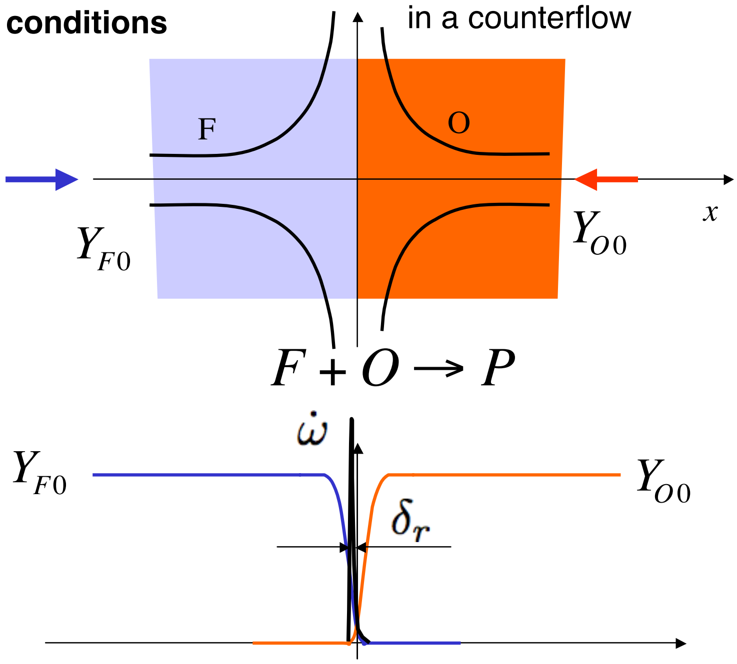
Issue 5 : Flames feature critical conditions

Strained non-premixed flame in a counterflow



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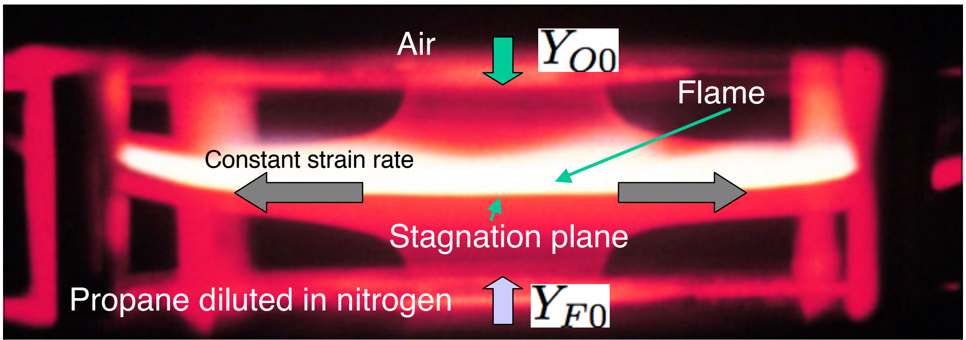
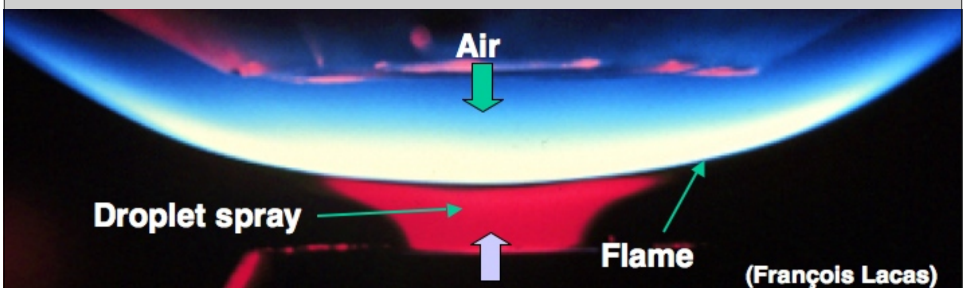
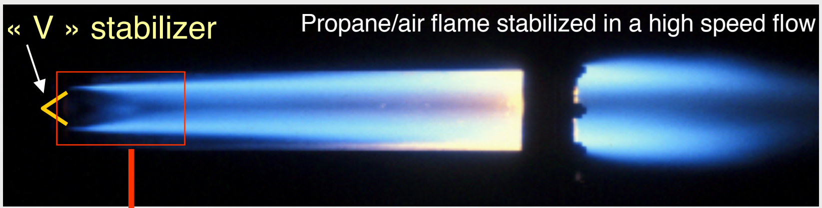


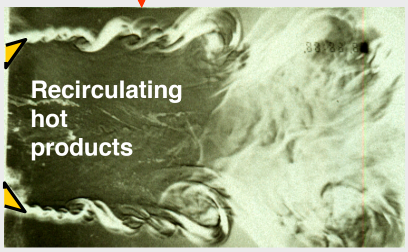
Strained flame formed in a counterflow of air and propane



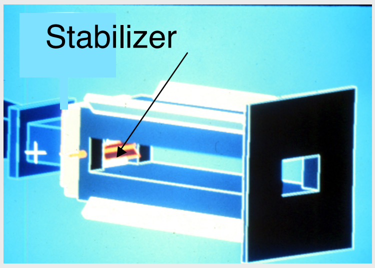
Strained flame by formed by a counterflow of air and heptane droplet spray

Issue 9 : Interaction between turbulence and reaction constitutes a central problem





Schlieren view of recirculating flow near the stabilizer lips



Combustor

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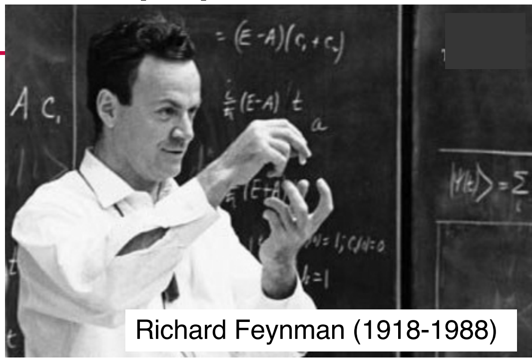
Flows of practical interest in propulsion are turbulent

According to **Richard Feynman**, famous Physics Nobel prize, « Turbulence is the most important unsolved problem of classical physics »



Richard Feynman (1918-1988)

Turbulent combustion introduces further difficulties with a range of spatial and temporal scales. In practical configurations this is compounded with other complexities : injection of fuel as a spray, rotation imparted to the flow by swirlers, multiperforation of the boundary…

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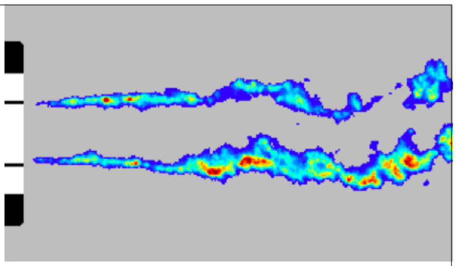
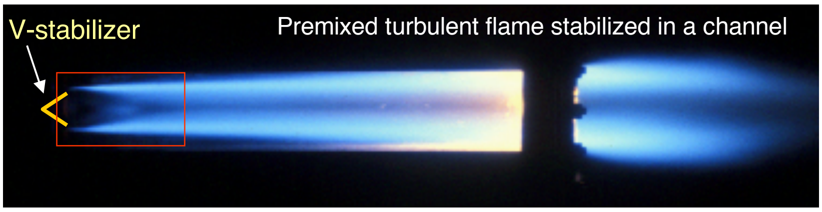
Some key issues

- Turbulent flame regimes and structures
- Processes controlling the mean reaction rate
- Models that suitably describe turbulence / kinetics interactions
- Simulation methods for high performance computing



Laser induced fluorescence imaging of OH radicals in a cryogenic flame formed by liquid oxygen and gaseous methane (p= 20 bar)



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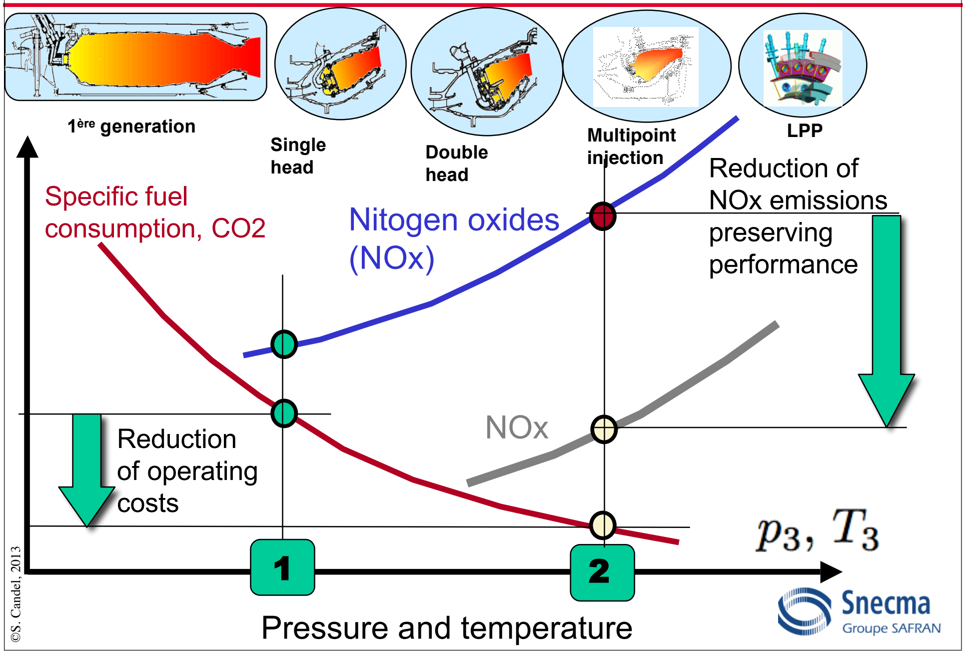
Major difficulties in coping with the energy and environmental challenges in aeroengines



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Simulation is crucial to the development of advanced combustion concepts

Direct simulation	Large eddy simulation	Reynolds average Navier-Stokes equations
All temporal and spatial scales are calculated	Large scales are calculated, small scales are represented by subgrid scale models	Equations are averaged and Reynolds stresses and turbulent fluxes are modeled

Laboratory → Applications

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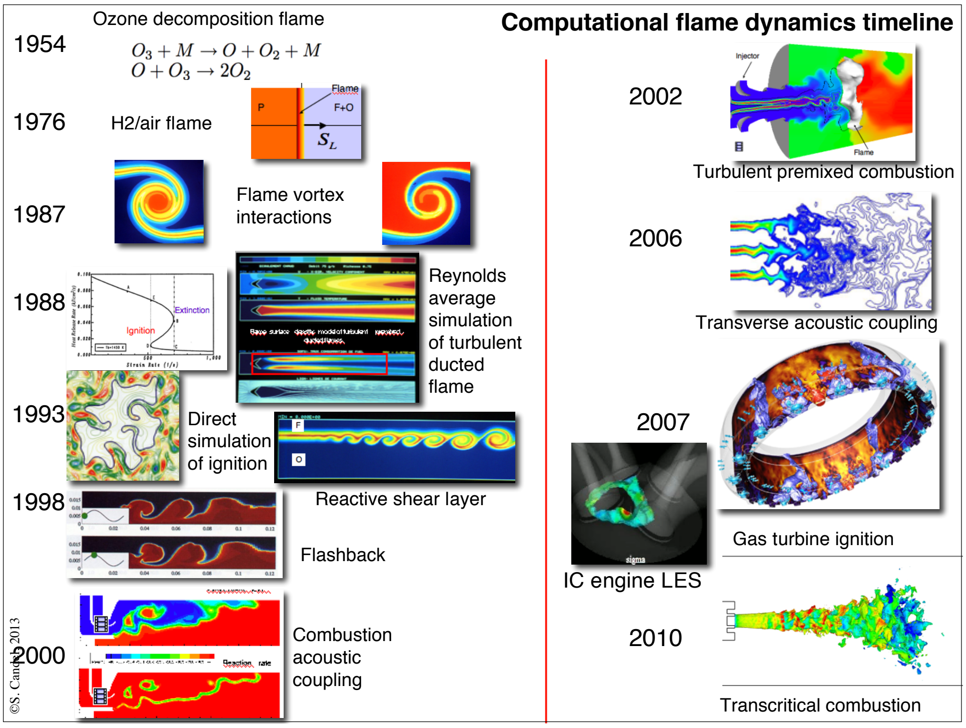
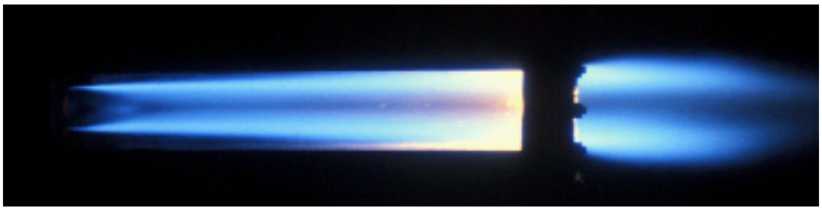


RANS modeling of turbulent combustion



Algebraic models	Probability density function models	Flamelet models
Rate of reaction controlled by mixing time $\bar{\dot{\omega}} = C_{EBU}\frac{\epsilon}{k}[\overline{Y'2}]^{1/2}$	The pdf determines the reaction rate $P(c)$ Probability density function $\overline{\rho}\widetilde{\dot{\omega}} = \int \rho\dot{\omega}(c)P(c)dc$	Local flame structure is similar to that of a laminar flame $\bar{\dot{\omega}} = \dot{m}\Sigma$ FSD transport equation $\frac{\partial \Sigma}{\partial t} + v_i\frac{\partial \Sigma}{\partial x_i} = \mathcal{D} + \mathcal{P} - \mathcal{A}$

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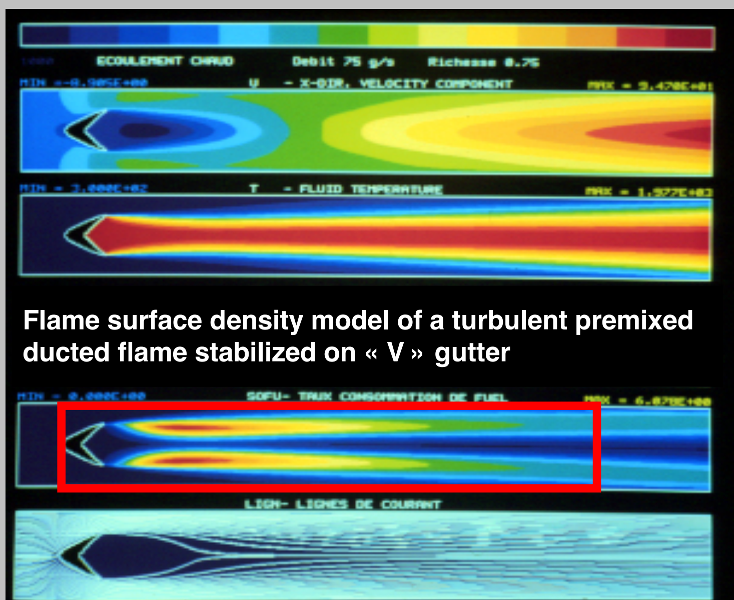
Typical RANS flamelet calculation of a turbulent ducted flame

u-component

Temperature

Consumption rate

Streamlines



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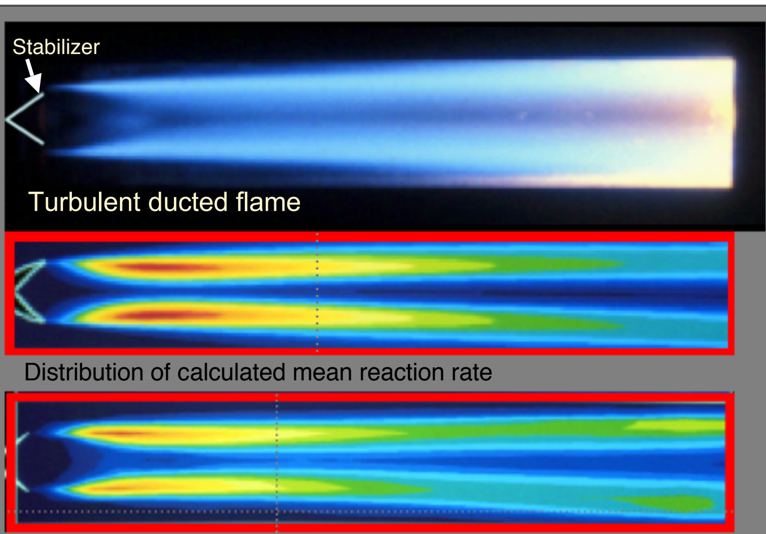
Candel, S., Veynante, D., Lacas, F., Maistret, E., Darabiha, N. & Poinsot, T. 1990 Coherent flame model: applications and recent extensions. In *Advances in combustion modeling*. Series on advances in mathematics for applied sciences (ed. B. Ed. Larrouturou), pp. 19–64. World Scientific, Singapore.



Distribution of calculated mean reaction rate

Distribution of reaction rate deduced from light emission from free radicals CH*

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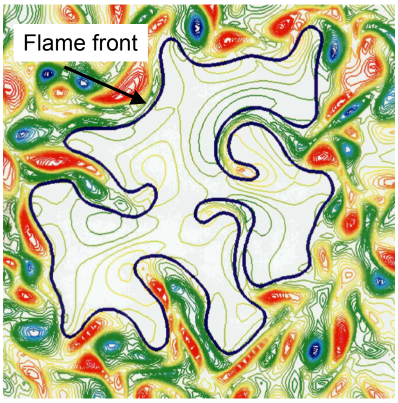
Comparison between mean reaction rates calculated with the Coherent Flame model (CFM) and determined experimentally from light emitted by free radicals CH*

It is generally believed that direct simulation can not be used to deal with practical configurations…



Ignition of a premixed flame in homogeneous turbulence (Poinsot, 1994)

…but DNS provides useful information on the fundamental processes controlling turbulent flames

$$Re_l = \frac{ul}{\nu}$$

Reynolds number at the large scale

$$Da = \frac{\tau_m}{\tau_c}$$

Damköhler number

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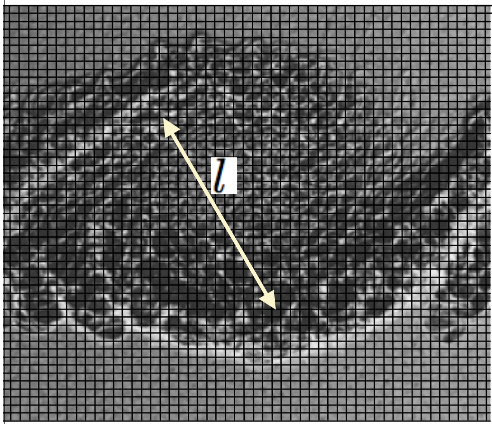
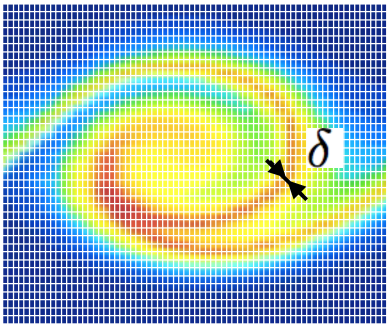
Direct simulation of premixed flames is feasible if…

Δx





A minimum of n points is used to discretize the flame

$$N\Delta x > l$$

$$\Delta x = l_k$$

$$\delta = n\Delta x$$

$$\frac{N}{n} > \frac{l}{\delta}$$

$$N > (\mathrm{Re}_l)^{3/4}$$

$$(N/n)^2 > \mathrm{Re}_l \mathrm{Da}$$

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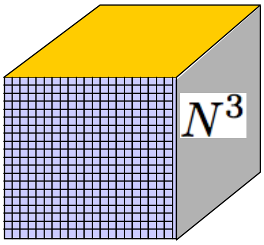
This limits direct simulation to low Reynolds and Damköhler numbers

$$N = 1000 \qquad N^3 = 10^9$$

$n = 20$ to resolve the flame



$$\mathrm{Re}_l < N^{4/3} = 10^4$$

$$\mathrm{Re}_l \mathrm{Da} < (N/n)^2 = 2500$$

If one chooses $\mathrm{Re}_l = 250$

then $\mathrm{Da} < 10$

In simulations of turbulent flames at Damköhler numbers greater than unity (typical of combustion conditions where the chemical time is short compared to the mechanical time) the Reynolds number can only take moderate values

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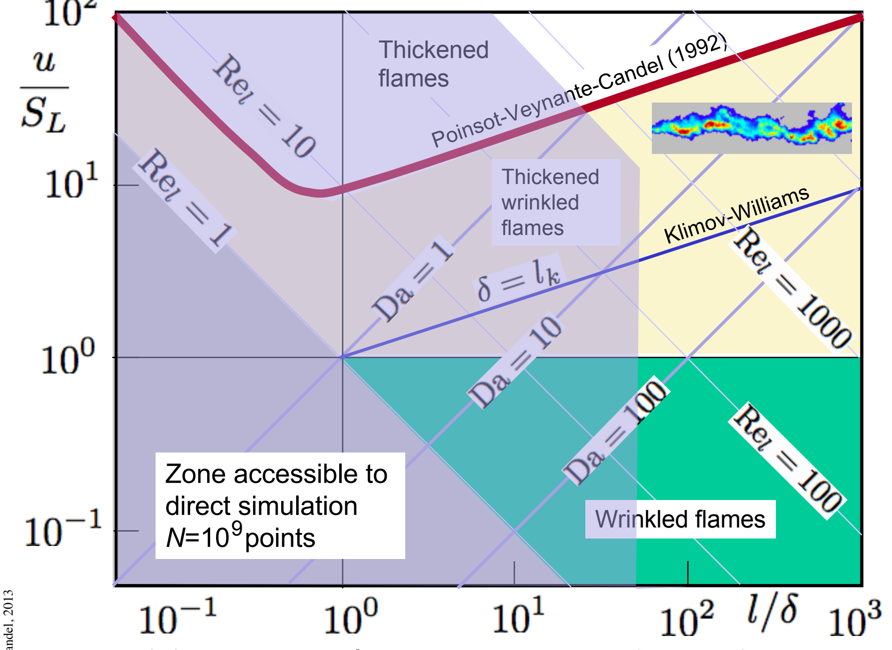
This restricts the domain accessible to direct simulation



T. Poinsot, S. Candel and A. Trouvé (1996) *Progress in Energy and Combustion Science.* **21**, 531-576.
Direct numerical simulation of premixed turbulent combustion.

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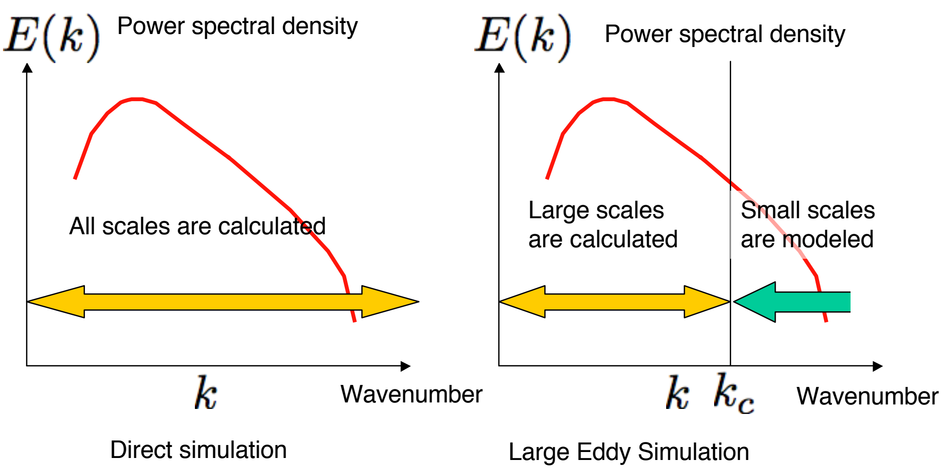
The future clearly lies in Large Eddy Simulations



$$k_c \simeq 1/\Delta$$

DNS

LES

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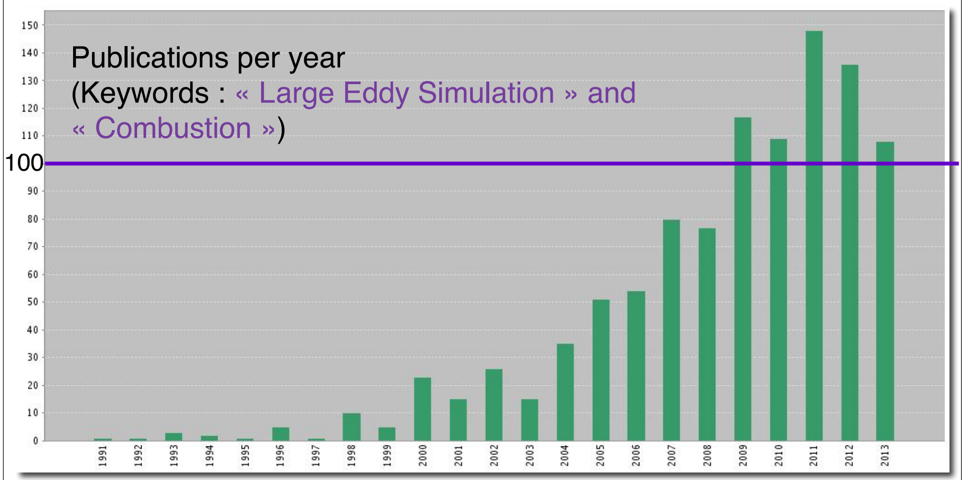
(1) Much of the current modeling effort in combustion is carried out in the LES framework



Over one hundred publications per year featuring these two keywords

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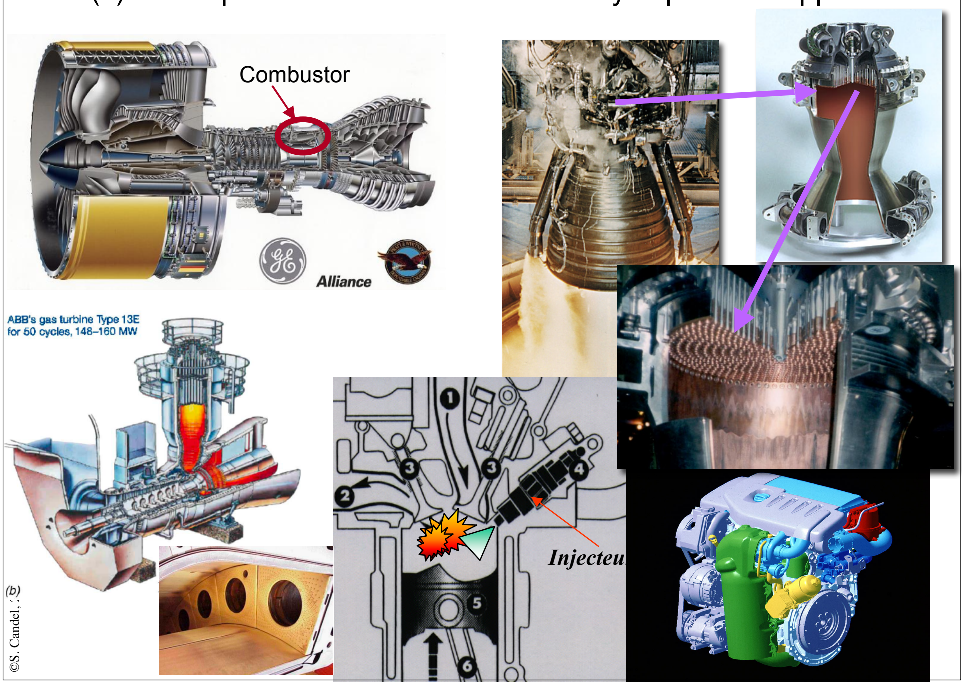
(2) It is hoped that LES will allow to analyze practical applications



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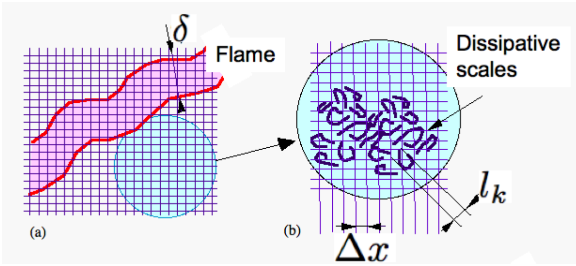
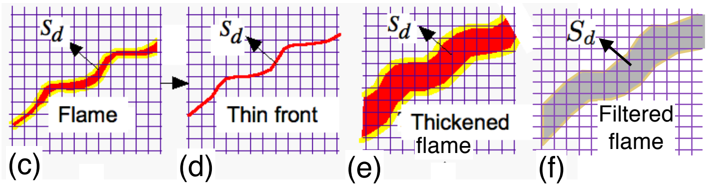
Large eddy simulation of turbulent combustion



In direct simulation, dissipative scales and flame must be resolved on the grid



In large eddy simulations the small scales are modeled but the grid is too rough to resolve the flame :

- The flame is replaced by a thin front (d)
- The flame is artificially thickened (e)
- The flame is spatially filtered (f)

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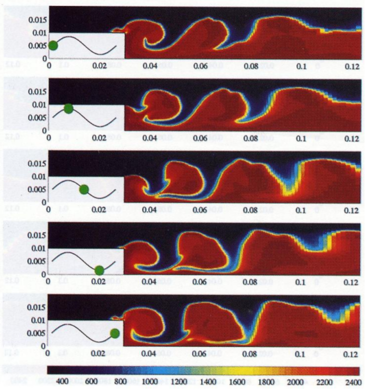
Artificial flame thickening

One effective method, for premixed combustion, relies on the artificial thickening of the flame so that it can be calculated on a relatively coarse grid.



- Originally proposed by Bracco and O'Rourke (1979) in a different context
- Later explored by Thibaut and Candel (1998) in a simulation of oscillations in a dump configuration
- Improved by Colin et al (2000) to account for subgrid scale wrinkling and enhanced chemical conversion

P. J. O'Rourke, F. V. Bracco, Two scaling transformations for the numerical computation of multidimensional unsteady laminar flames, *Journal of Computational Physics* 33 (1979) 185–203.

D. Thibaut, S. Candel, Numerical study of unsteady turbulent premixed combustion. application to flashback simulation., *Combustion and Flame* 113 (1998) 51–65.

O. Colin, F. Ducros, D. Veynante, T. Poinsot, A thickened flame model for large eddy simulations of turbulent premixed combustion, *Physics of Fluids* 12 (7) (2000) 1843–1863.

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Thickened flame model (TFLES)

$$\frac{\partial \rho c}{\partial t} + \nabla \cdot (\rho \mathbf{u} c) = \nabla \cdot (\bar{\rho} D \nabla c) + \rho \dot{\omega}_c$$

$$\dot{\omega}_c \longrightarrow \dot{\omega}_c / F \quad D \longrightarrow DF$$

The flame thickness is multiplied by F

Include Ξ to represent flame surface wrinkling at the subgrid scale

$$\frac{\partial \bar{\rho} \hat{c}}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \hat{c}) = \nabla \cdot (\bar{\rho} D \Xi F \nabla \hat{c}) + \frac{\rho \dot{\omega}_c \Xi}{F}$$

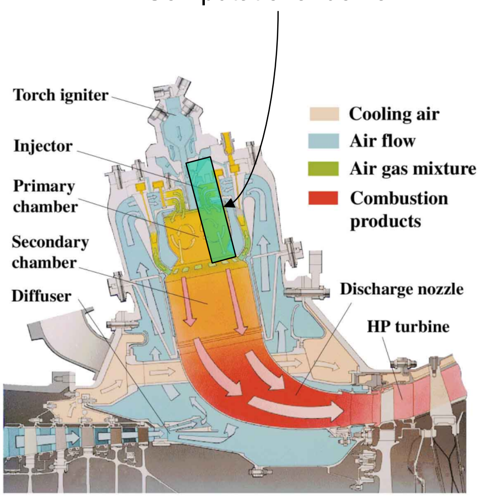
The front moves at $S_\Delta = \Xi S_l$ The flame is thickened by F

Colin, O., Ducros, F., Veynante, D. & Poinsot, T. 2000 A thickened flame model for large eddy simulations of turbulent premixed combustion. *Physics Fluids A* 12 (7), 1843 – 1863.

©S. Candel, 2013

Early calculations of gas turbine combustion dynamics

Computational domain



Premixed combustor of modern gas turbines

Simulation must account for the complexity of turbulent combustion, rotating flow, complex geomeytry, coupling with acoustics and dynamical response of upstream and downstream elements

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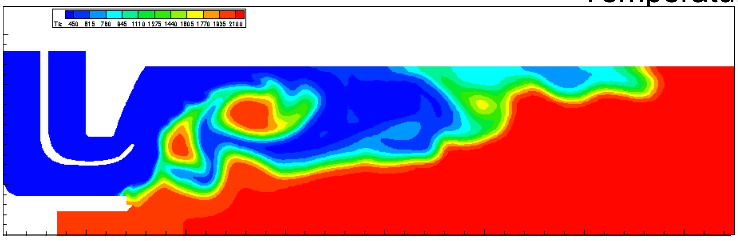
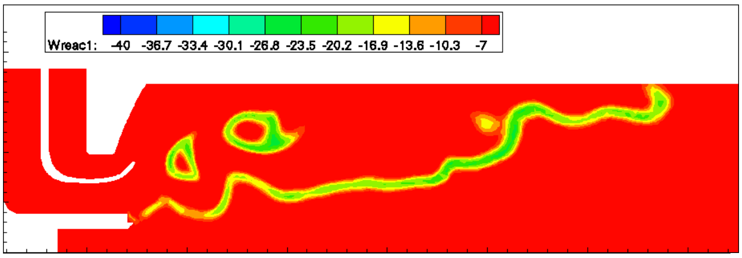
Combustion dynamics in premixed turbulent combustors

Temperature



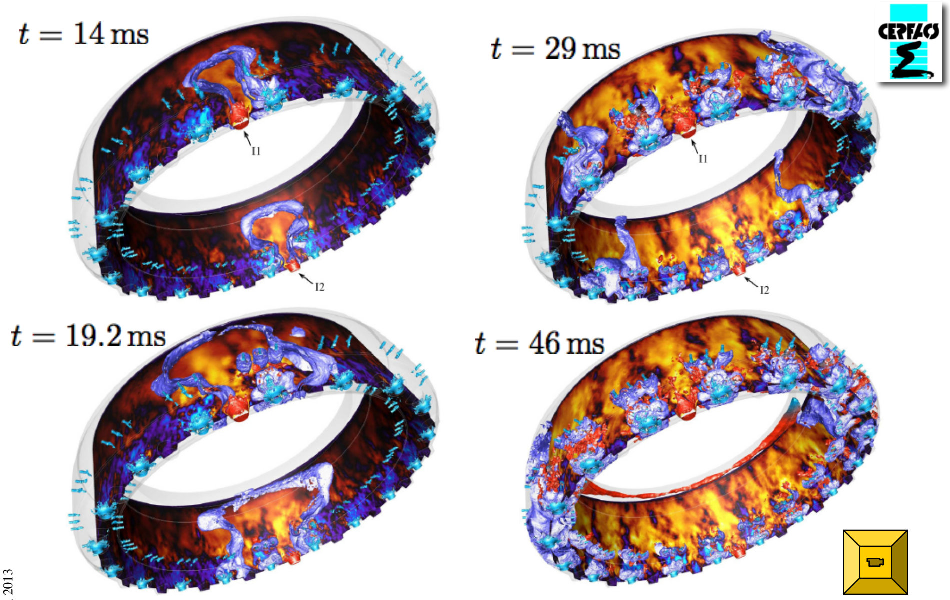
Heat release rate



©S. Candel, 2013

S. Ducruix, T. Poinsot and S. Candel (2002) Large eddy simulation of combustion instabilities in a swirled combustor. *In Turbulent mixing and combustion,* A. Pollard and S. Candel, eds. Kluwer, Dodrecht, Chapter 31, pp. 357-366.

A recent LES of ignition in a gas turbine configuration

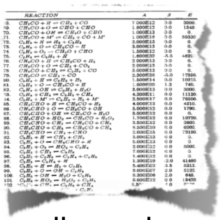


©S. Candel, 2013

M. Boileau, G. Staffelbach, B. Cuenot, T. Poinsot and C. Bérat (2008) *Combust. Flame* 154, 2-22. LES of ignition in a gas turbine engine.

Computing turbulent reactive flows with tabulated chemistry

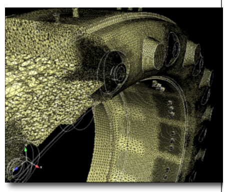
Chemistry tabulation



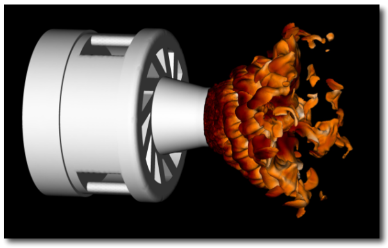
n_{sp} dimensions

Chemical table

Coupling with flow solver



Combustion modeling and filtering



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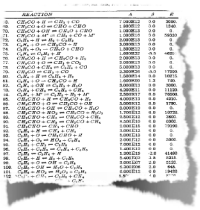
Tabulated chemistry



The chemical state is formally defined by

$$\varphi = \mathcal{F}(p, T, \underbrace{Y_1, ..., Y_{n_s}}_{\text{Composition space}})$$

In practice, only a reduced part of the composition space is accessed. The composition space can then be reduced to

$$\varphi = \mathcal{F}'(p, T, \psi_1, ..., \psi_n) \qquad n << n_s$$

Initially invariant manifold identified by mathematical analysis

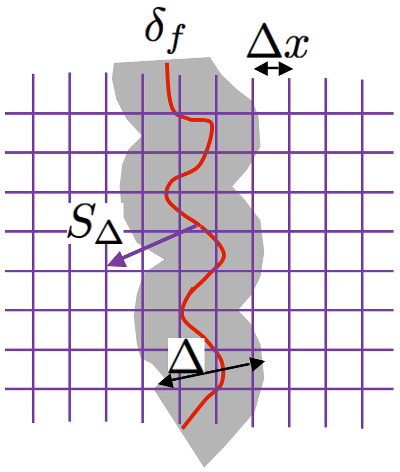
ILDM **Maas, U. and Pope,** S. 1992 Simplifying chemical kinetics: Intrinsic low-dimensional manifolds in composition space. *Combustion and Flame* 88, 239–264.

More recent manifold identification based on physical analysis (typically using flamelet concepts)

FPI **Gicquel, O., Darabiha, N. and Thévenin**, D. 2000 Laminar premixed hydrogen / air counterflow flame simulations using flame prolongation of ILDM with differential diffusion. *Proc. Combust. Inst.* 28, 1901–1908.

FGM **van Oijen, J. A., Lammers, F. A.&de Goey, L. P. H.** 2001 Modelling of complex premixed burner systems by using flamelet-generated manifolds. *Combust. Flame* 127 (3), 2124–2134.

Flame filtering in LES



fresh gases

burnt gases

$$\Delta > \Delta x > \delta_f$$

LES filter size > mesh size> flame thickness

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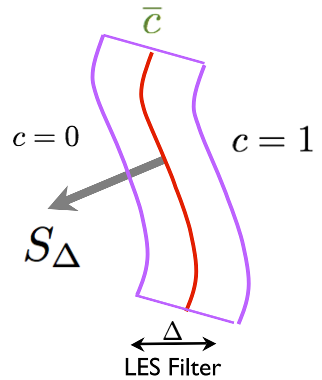
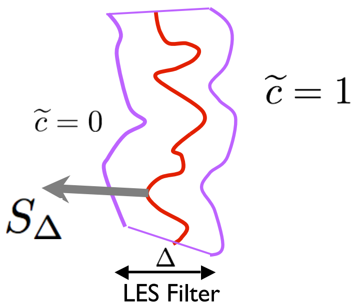


If no subgrid scale flame wrinkling

$$\overline{\rho}_0 S_l = \int_{-\infty}^{+\infty} \rho \dot{\omega}_c \left(c(x_n) \right) dx_n$$

Filtered flame front velocity

$$S_\Delta = S_l$$



With subgrid scale flame wrinkling

Flame wrinkling

$$\Xi = \frac{\overline{|\nabla c|}}{|\nabla \overline{c}|}$$

Filtered flame front velocity

$$S_\Delta = \Xi S_l$$

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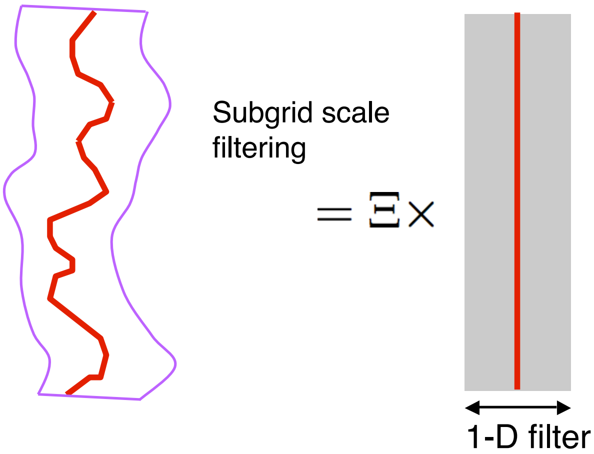
Flamelet hypothesis: the filtered flame has the structure of a wrinkled 1-D filtered flame



$$\overline{\rho}\widetilde{\dot{\omega}}_{Y_c} = \Xi \int_{-\infty}^{\infty} \rho^* \dot{\omega}^*_{Y_c} G_\Delta(x_n - x'_n) dx'_n$$

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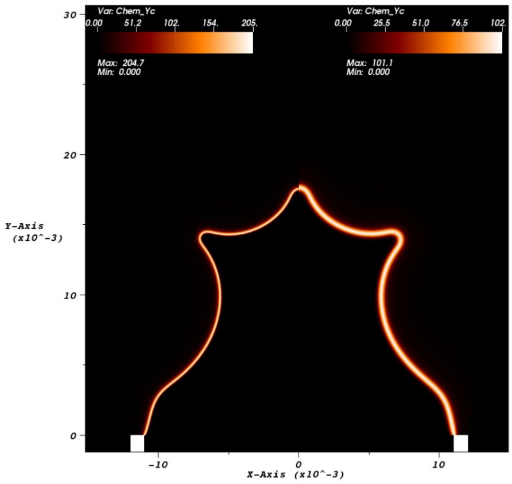
Computational test in the absence of subgrid scale wrinkling



Direct simulation F-TACLES

F-TACLES

$$\overline{\dot{\omega}}_c = \int_{-\infty}^{+\infty} \dot{\omega}_c G_\Delta(x - x')dx'$$

where G is a Gaussian filter

Fiorina, B., Vicquelin, R., Auzillon, P., Darabiha, N., Gicquel, O. &Veynante, D. 2010 A filtered tabulated chemistry model for LES of premixed combustion. *Combust. Flame* 157, 465–475.

There is a near perfect match between the fully resolved flame (left) and the filtered Flame (right)

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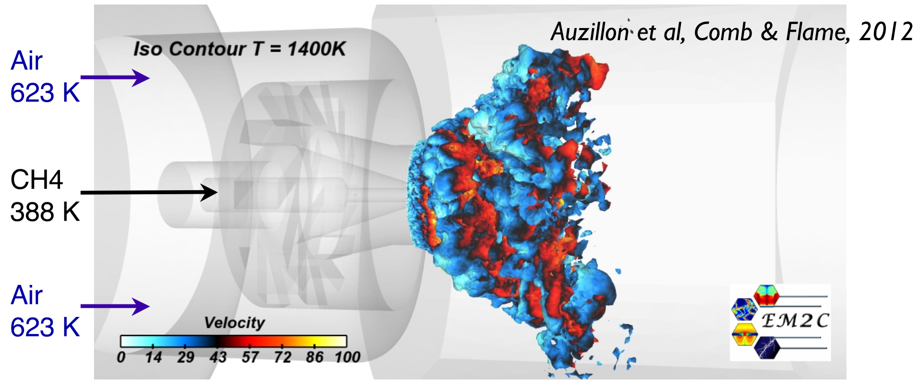
MOLECULES swirling flame

TUDarmstadt experiments: Janus et al. 2005
TUDarmstadt numerical simulations: Wegner et al. 2007, Schneider et al. 2008

AVBP code, TTGC scheme (3rd Order), WALE model
Tabulated Thermochemistry for Compressible flows formalism

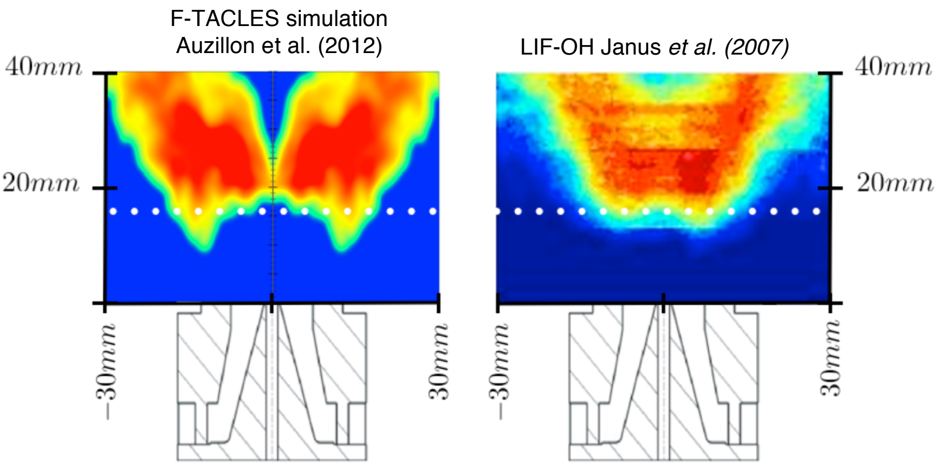


8.1 million nodes, 40.2 million cells, $(\Delta x)_{min}$= 0.08 mm
180 000 CPU hours (2000 cores) $\Phi = 0.8$

Vicquelin, R., Fiorina, B., Payet, S., Darabiha, N. & Gicquel, O. 2011 Coupling tabulated chemistry with compressible CFD solvers. *Proc. Combust. Inst.* 33 (1), 1481–1488.

©S. Candel, 2013

Flame structure: average OH molar fraction



Dimensionless OH molar fraction

Auzillon, P., Gicquel, O., Darabiha, N., Veynante, D. and Fiorina, B. 2012 A filtered tabulated chemistry model for LES of stratified flames. *Combust. Flame* 159, 2704 – 2717.

Janus, B., Dreizler, A. and Janicka, J. 2007 Experiments on swirl stabilized non-premixed natural gas flames in a model gasturbine combustor. *Proc. Combust. Inst.* 31, 3091 – 3098.

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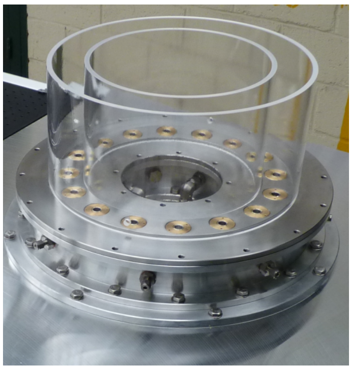
The current trend is to move from simple flame configurations to more complex systems…

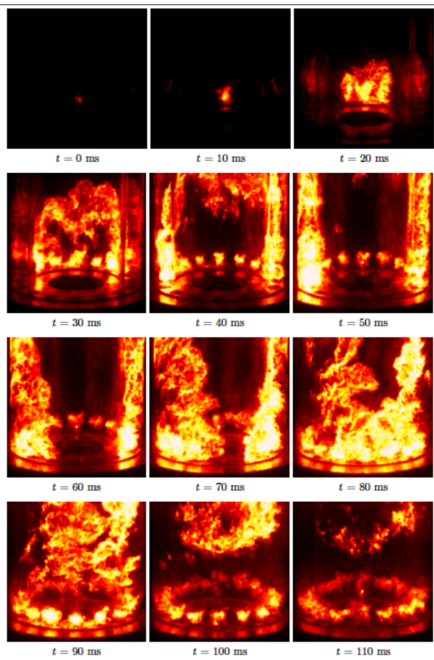
Steady state operation of the MICCA2 multiple injector combustor

©S

MICCA2 annular combustor



- Annular geometry
- Multiple swirling injectors
- Premixed (propane/air)
- Atmospheric pressure



J.F. Bourgouin, D. Durox, T. Schuller, J. Beaunier and S. Candel (2013) *Combust. and Flame*, 160, 1398-1413. Ignition dynamics of an annular combustor equipped with multiple swirling injectors.

©S. Candel, 2013

Ignition dynamics

High speed imaging

Frame rate
$f_c = 1/6000\,\mathrm{s}$

Exposure time
$\tau = 16.6\,\mu\mathrm{s}$

Operating conditions

Bulk velocity
$U_b = 12.2\,\mathrm{m/s}$

Equivalence ratio
$\phi = 0.76$

Thermal power
$P_{th} = 40\,\mathrm{kW}$

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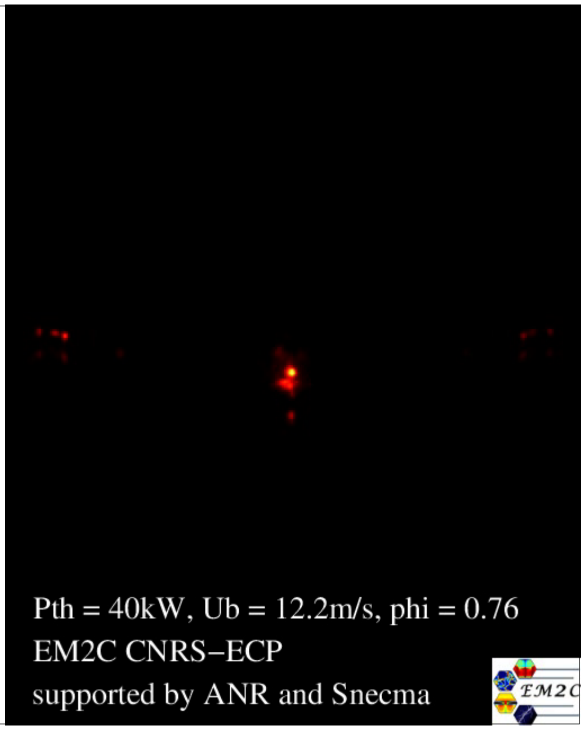
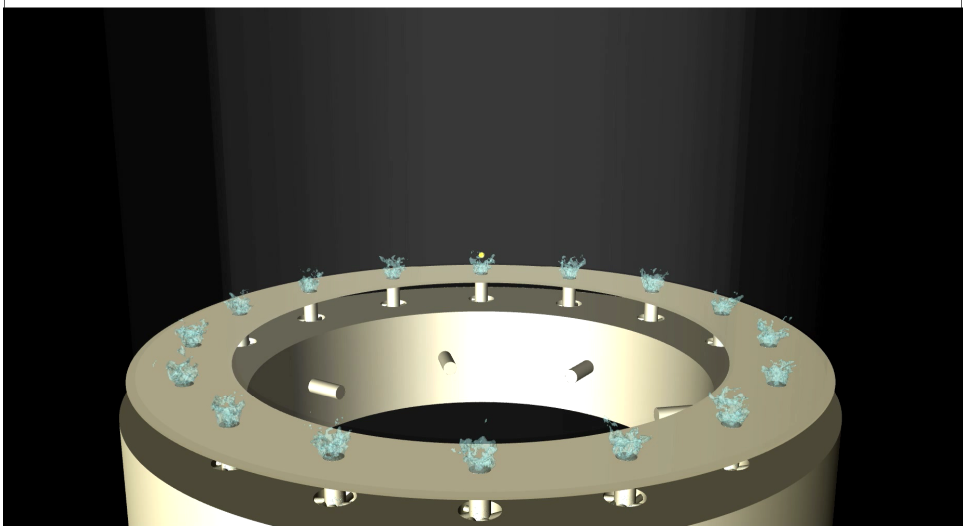
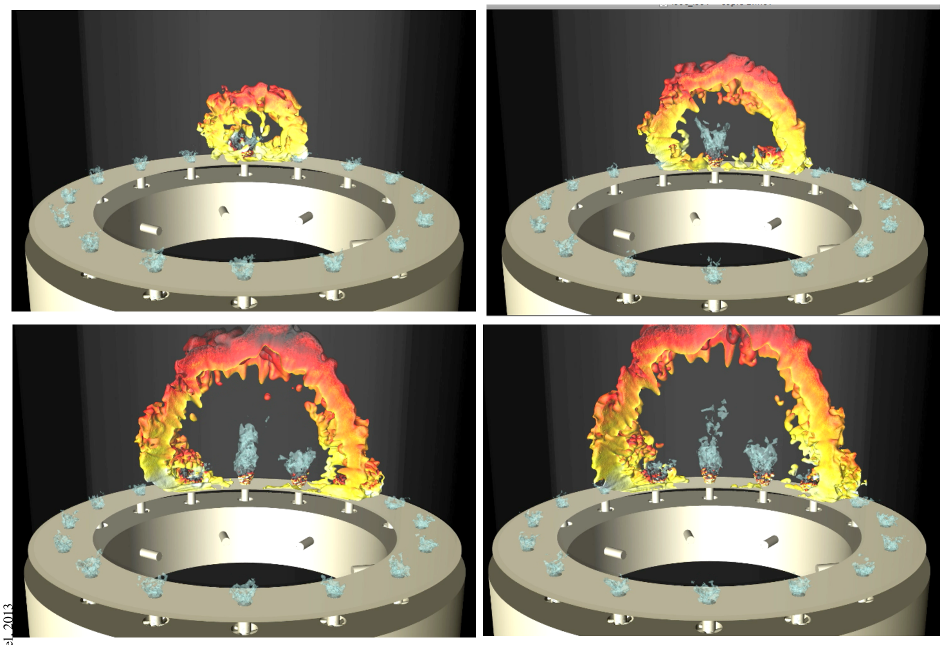


Ignition dynamics simulation



M. Philip, M. Boileau, T. Schmitt, R. Vicquelin, S. Candel (2013) Simulation of ignition mechanisms in annular multi-injectors combustors and comparison with experiments. *14th International conference on numerical combustion, San Antonio.*

©S. Candel, 2013



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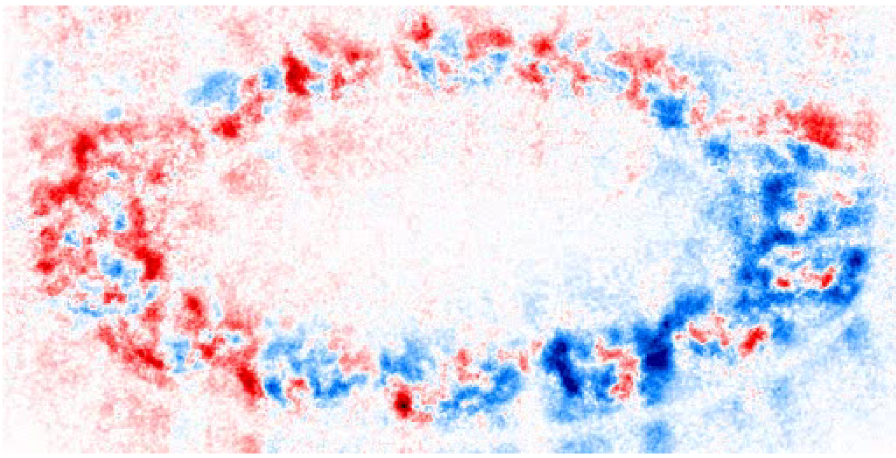
Four instants during the light-around process

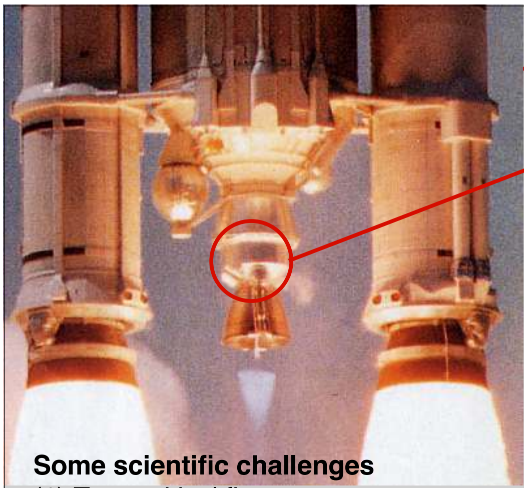
Standing mode

Flame dynamics coupled by the 1A1L mode at a frequency *f*=792 Hz



©S. Candel, 2013

J.F. Bourgouin, D. Durox, T. Schuller, J. Moeck and S. Candel (2013) ASME Paper GT 2013-95010. Self-sustained Instabilities in an Annular Combustor Coupled by Azimuthal and Longitudinal Acoustic Modes.



Space propulsion

Important technical and economic challenges

Reliability and cost reduction objectives

Need for knowledge and simulation tools for new developments

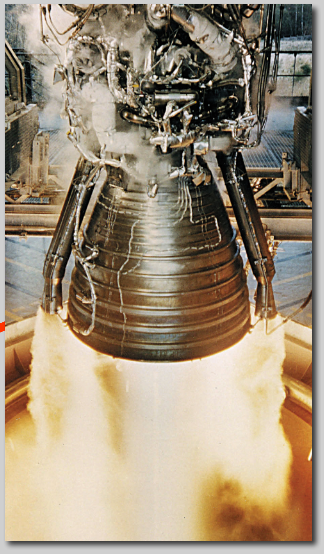
Some scientific challenges

(1) Transcritical flame structures
(2) Stabilization mechanisms and criteria
(3) Effects of injection geometry and operating parameters
(4) Transient operation and instabilities
(5) Transcritical range modeling and simulation

Some technological challenges

(1) Performance, reliability…
(2) Transient operation control
(3) Prediction and suppression of instabilities
(4) Thrust chamber life extension
(5) Cost reduction

©S. Candel, 2013



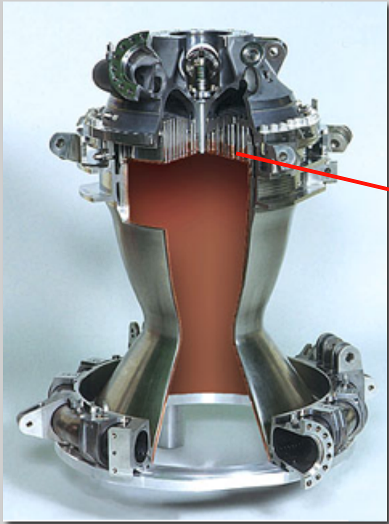
Pressure reaches 110 bar (11 MPa) in rocket engine thrust chambers while injection temperature is low

$p_c(O_2) = 50.4$ bar

$$P = 2.5\,\mathrm{GW}$$
$$V = 50\,\mathrm{litres}$$
$$P/V = 50\,\mathrm{GW\ m^{-3}}$$

©

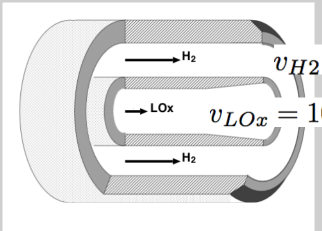
Injection technology in cryogenic engines



Cryogenic engine thrust chamber

$2.5\ \mathrm{GW} \quad 50\ \mathrm{GW\ m^{-3}}$

Chamber backplane comprises 516 injecteurs

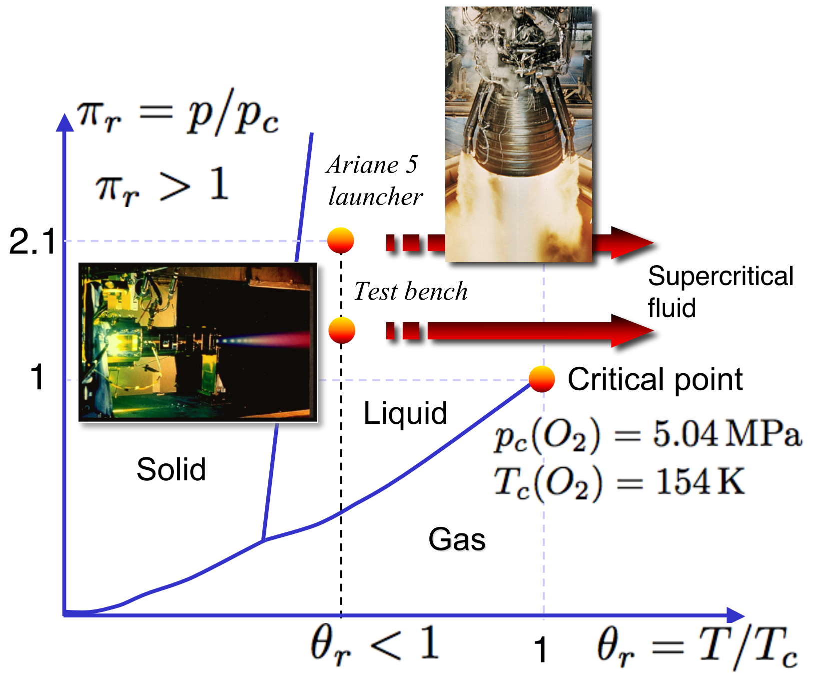


$v_{H2} = 200\,\mathrm{m\ s^{-1}}$

$v_{LOx} = 10\,\mathrm{m\ s^{-1}}$

Schematic view of a single injector

lel, 2013



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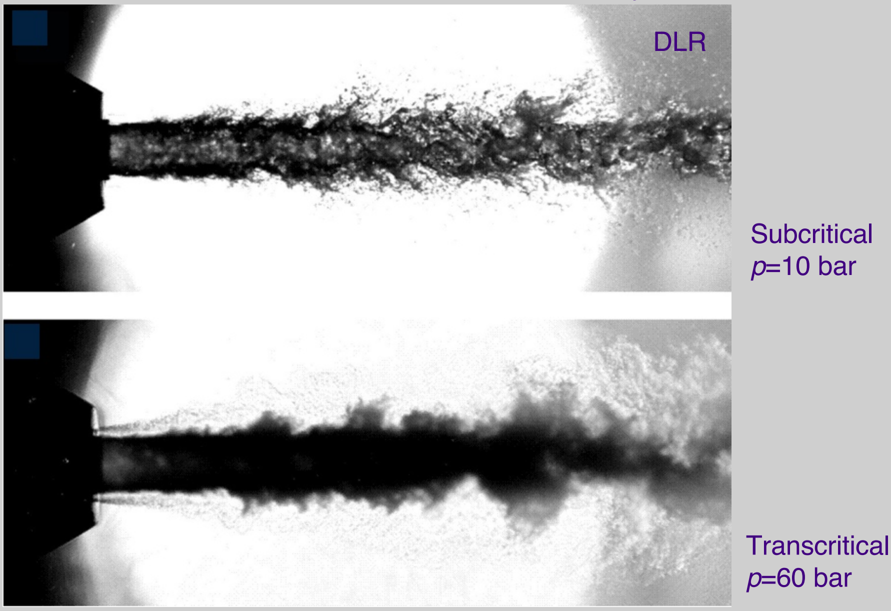
Coaxial injection of LN2 and He



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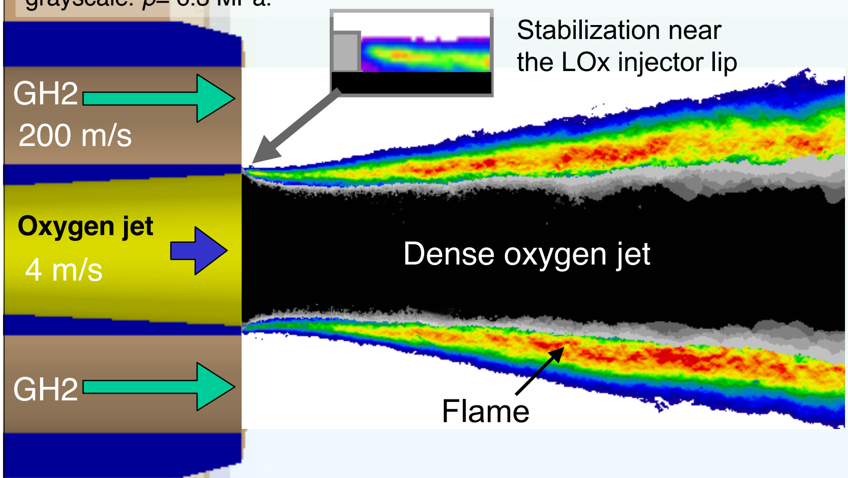
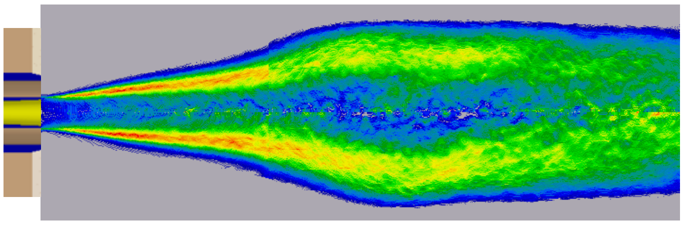
Backlighting images of coaxial injection of nitrogen surrounded by an annular jet of helium. Top: subcritical injection at a pressure of 1 MPa. Bottom : transcritical injection ofnitrogen at a pressure of 6 MPa.

Image of the transcritical flame formed between liquid oxygen and gaseous hydrogen. A slice of the Abel transform of the average OH* emission intensity is shown in color. The average oxygen jet position is obtained by backlighting and shown on a grayscale. *p*= 6.3 MPa.



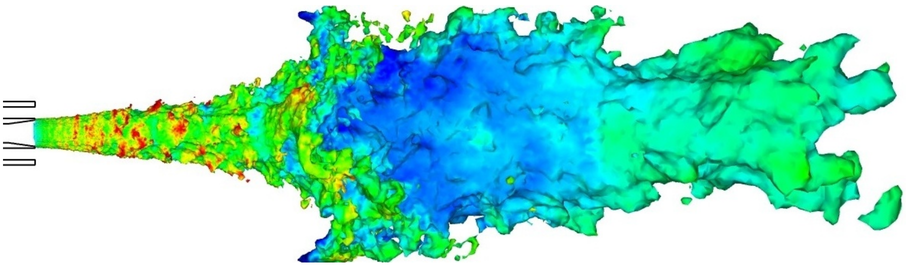
M. Juniper, A. Tripathi, P. Scouflaire, J. Rolon, S. Candel (2000) *Proceedings of the Combustion Institute* 28, 1103-1110. Structure of cryogenic flames at elevated pressures,

Transcritical combustion LOx/GH2



Average flame structure

Abel transform of average emission image. A60, LOx/GH2, *p* = 60 bar, *J=12*



Iso-surface of temperature (2000 K) of a transcritical oxygen / supercritical hydrogen coaxial flame (case A60 of Juniper et al. 2000) colored by axial velocity (dark blue: -50 m/s; red: 150 m/s).

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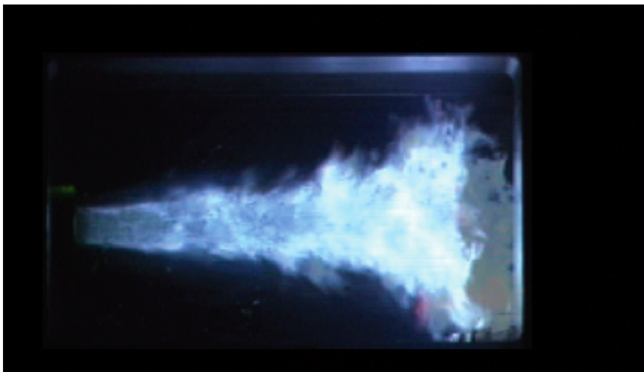
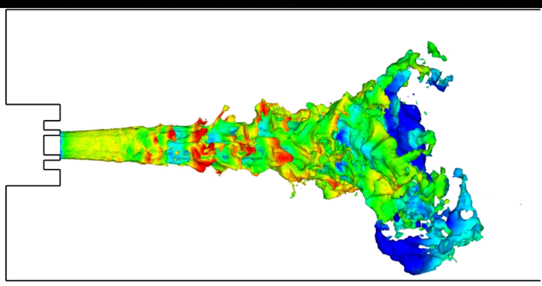
Transcritical combustion simulation



Direct visualization of a liquid oxygen gaseous methane flame under transcritical conditions *p*=56 bar (5.6 Mpa)



Result of large eddy simulation. Temperature isosurface colored by velocity levels

AVBP-RG

T. Schmitt, Y. Méry, M. Boileau and S. Candel (2011) *Proc. Combust. Inst*. 33. 1383-1390. Large eddy simulation of oxygen/methane flames under transcritical conditions.

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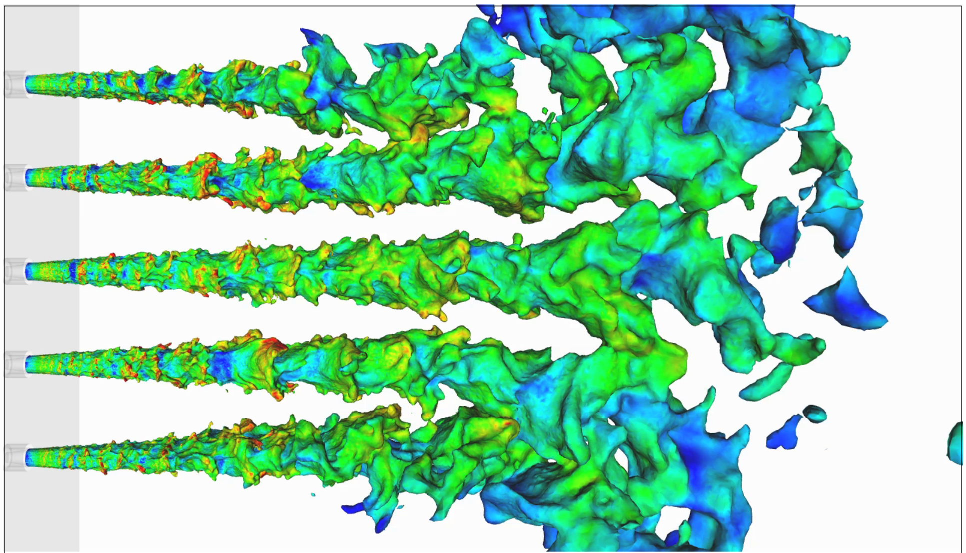

Large eddy simulation of cryogenic flames in the multiple injector combustor (MIC). Pressure is above critical.

AVBP-RG

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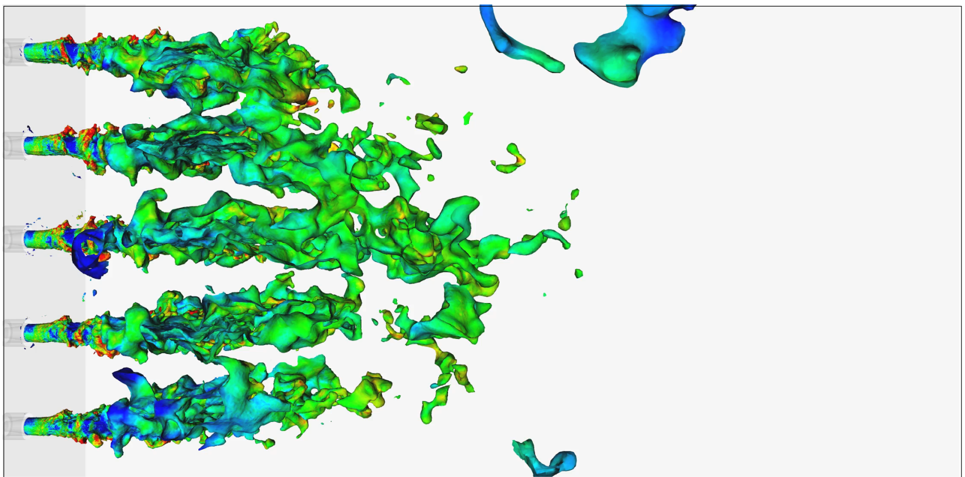
LES-HF Project team (EM2C-Cerfacs)



AVBP-RG

Large eddy simulation of cryogenic flames in the multiple injector combustor (MIC). Pressure is above critical. Flames interact with the 1T1L mode Induced by the Very High Amplitude Modulator (VHAM)

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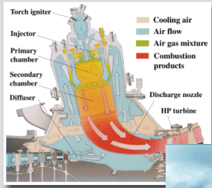
Conclusions and challenges

- With significant advances in theory, experiment and simulation, combustion has reached a remarkable degree of maturity but problems have become progressively more complex



- Progress is quite substantial in CFD but improvements are needed in submodels
  - Flame descriptions including detailed chemistry
  - Subgrid combustion models
  - Spray models
  - Acoustic boundary conditions…

- Validations under well controlled conditions

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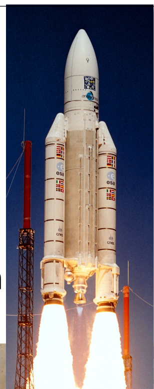
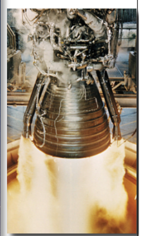
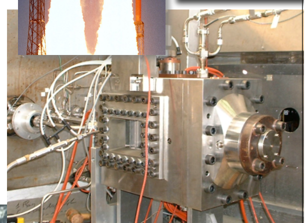
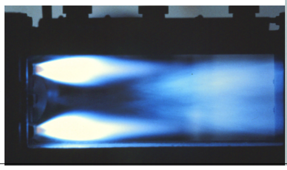
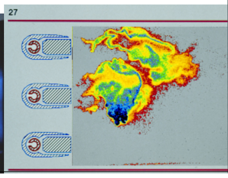
- Future research focused on
  - Computational flame dynamics under realistic conditions
  - Combustion dynamics in multiple injector annular systems (ignition, extinction, flashback, instabilities…)
  - High pressure and transcritical combustion
  - Break-up atomization and spray flames
  - Dynamic control development and simulation
  - Computational efficiency, automatic reduction, tabulation, code coupling, multiphysics problems…

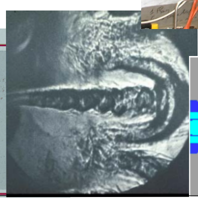


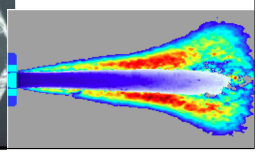












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