Combustion dynamics
Lecture 10c
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Computational Flame Dynamics

Historical perspective (RANS, DNS, LES)
Laminar flame dynamics
Large eddy simulation of turbulent flames
Ignition of annular combustors
Annular systems azimuthal instabilities
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Trends in computational flame dynamics

1960

CFD beginnings (Computational Fluid Dynamics)

1970

Numerical combustion

2000

New CFD (Computational Flame Dynamics)

Simulation is crucial to the development of advanced combustion concepts

Direct simulation

All temporal and spatial scales are calculated

Large eddy simulation

Large scales are calculated, small scales are represented by subgrid scale models

Reynolds average Navier-Stokes equations

Equations are averaged and Reynolds stresses and turbulent fluxes are modeled

Laboratory

Applications
Ozone decomposition flame

\[ \text{O}_3 + \text{M} \rightarrow \text{O} + \text{O}_2 + \text{M} \]

\[ \text{O} + \text{O}_2 \rightarrow 2\text{O}_3 \]

\[ \text{H}_2/\text{air flame} \]

Flame vortex interactions

Reactive shear layer

Flashback

Combustion acoustic coupling

Direct simulation of ignition

Reynolds average simulation of turbulent ducted flame

Computational flame dynamics timeline

2002
Turbulent premixed combustion

2006
Transverse acoustic coupling

2007
IC engine LES

Gas turbine ignition

2010
Transcritical combustion

2011
Calculated rotating mode in an annular combustor

2012
Multiple cryogenic jets under transverse modulation

2013
Ignition dynamics of an annular combustor

2015
Triggered combustion instability of a full rocket engine (42 injectors)
Large Eddy Simulations in fluid mechanics (observed in the Web of Science)

Over two hundred publications per year featuring these two keywords:

Keywords: «Large Eddy Simulation» and «Combustion»

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

Over two hundred publications per year featuring these two keywords.
Direct simulation of premixed flames is feasible if... A minimum of \( n \) points is used to discretize the flame

\[
N \Delta x > l \\
\Delta x = l_k \\
N > (Re_l)^{3/4} \\
(N/n)^2 > Re_l Da
\]

This limits direct simulation to low Reynolds and Damköhler numbers

\[
N = 1000 \\
N^3 = 10^9 \\
n = 20 \quad \text{to resolve the flame} \\
Re_l < N^{4/3} = 10^4 \\
Re_l Da < (N/n)^2 = 2500
\]

If one chooses \( Re_l = 250 \) then \( Da < 10 \)

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.
Thickened flames

Wrinkled flames

Klimov-Williams

Poinsot-Veynante-Candel (1992)

This restricts the domain accessible to direct simulation

Zone accessible to direct simulation
$N=10^9$ points

Conical flame perturbed by equivalence ratio modulations

Inverted flame perturbed by equivalence ratio modulations

Direct numerical simulation of premixed turbulent combustion.

Combustion dynamics of flames interacting with equivalence ratio perturbations

Combustion dynamics of flames interacting with equivalence ratio perturbations

Conical flame perturbed by equivalence ratio modulations

Velocity field perturbed by equivalence ratio modulations


(a-e) Methane mass fraction distributions during a cycle. $\phi(t) = \phi_0 + \phi_1 \sin \omega t$

(f) Relative heat release and equivalence ratio perturbation

\[ f = 375 \text{ Hz}, \quad \phi' / \bar{\phi} = 0.1, \quad \phi = 0.8 \]
(2) It is hoped that LES will allow to analyze practical applications

The future clearly lies in Large Eddy Simulations

\[ E(k) \text{ Power spectral density} \]

\[ k \text{ Wavenumber} \]

\( k_c \approx 1/\Delta \)
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)

The thickened flame method

LES methods are now widely used to examine combustion dynamics and instabilities. LES naturally describes the flame motion induced by the large scales.

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

This method, originally proposed by Bracco and O'Rourke in a different context, was later explored by Thibaut and Candel (1998) in a simulation of oscillations in a dump configuration.

Combined with a subgrid scale efficiency function the flame thickening method (FTM) has been extensively exploited to investigate combustion dynamics in premixed gas turbine combustors.


Swirling flame calculations with LES and complex chemistry give access to practical applications.

Tabulated Thermochemistry for Compressible flows formalism (FTACLES)


AVBP

8.1 million nodes, 40.2 million cells, $(\Delta x)_{min} = 0.08$ mm 180 000 CPU hours (With 2000 cores the restitution time is about 1 week)

$\Phi = 0.8$
Ignition of an annular combustor

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

**Experiment**

**Simulation**


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Comparison between experimental and numerical flame configurations for liquid n-heptane injection. $\phi = 0.8, \mathcal{P} = 79.8 \text{ kW}$


Large Eddy Simulation of light-round in an annular combustor with liquid spray Injection and comparison with experiments

Multiple injector combustor (MIC) equipped with a Very High Amplitude Modulator (VHAM) mounted on the « Mascotte » cryogenic combustion testbench
Large eddy simulation of cryogenic flames in the multiple injector combustor (MIC).
Pressure is above critical.
Cryogenic flames are developing in the absence of acoustic modulation.

The transverse acoustic modulation induces a significant reduction in flame length.

Structure modale obtenue dans la chambre au moyen d’une simulation numérique de la modulation par le VHAM.
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

Simulation of a cryogenic engine comprising 42 coaxial injectors (BKD)


Power spectral density of a pressure signal in a regime of a high frequency instability (Operating point LP4)